Country Report of

Solar and **W**ind
Energy **R**esource
Assessment

BANGLADESH

Supported by

United Nations Environment Programme (UNEP)

Global Environment Facility (GEF)

Country Partner

Renewable Energy Research Centre (RERC)

University of Dhaka, Bangladesh

Final Report of

Solar and Wind Energy Resource Assessment (SWERA) - Bangladesh

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*with the support of members from the SWERA – Bangladesh group

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Preface

Reduction of global greenhouse gas emission to arrest global warming requires minimizing the use of fossil fuels. To achieve this a large scale use of renewable energies must be made over the globe for production of electrical and thermal energy. Success of wind and solar energy projects require detailed and precise information on the resources. For most developing countries adequate information on the resources are not available. UNEP supported by GEF has started a program to assess solar and wind resources for a number of countries including Bangladesh, China, Brazil, Nepal and Sri Lanka in the initial program.

World resources of oil, gas and coal are limited and there is a global concern about this but for Bangladesh the situation appears to be extremely unhappy as per capita reserve of fossil fuels is only $1/50^{th}$ to $1/100^{th}$ of world per capita. A close look at Bangladesh energy scenario is presented before going to an overview of the results of resource assessments for wind and solar energy under the SWERA Program carried out for Bangladesh with RERC as the local partner. Data and maps for Bangladesh are available in the SWERA website. Details of assessment techniques and results will be presented in the following sections together with the possible applications of the resources.

A spin-off from the SWERA Project is development of manpower trained at home and abroad in WAsP techniques, RETScreen and HOMER analyses and the capability development for using GIS Toolkit.

NREL, RISOE and DLR produced modeled maps and data sets for Bangladesh and NREL developed the GIS Toolkit. RERC measured and collected ground data and standardized the maps and data sets.

Mr. Tom Hamlin of UNEP who has been the project manager for SWERA activities always extended his helping hands to RERC which enabled the completion of the project. TERI has played a vital role as the Regional Coordinator.

Section 1

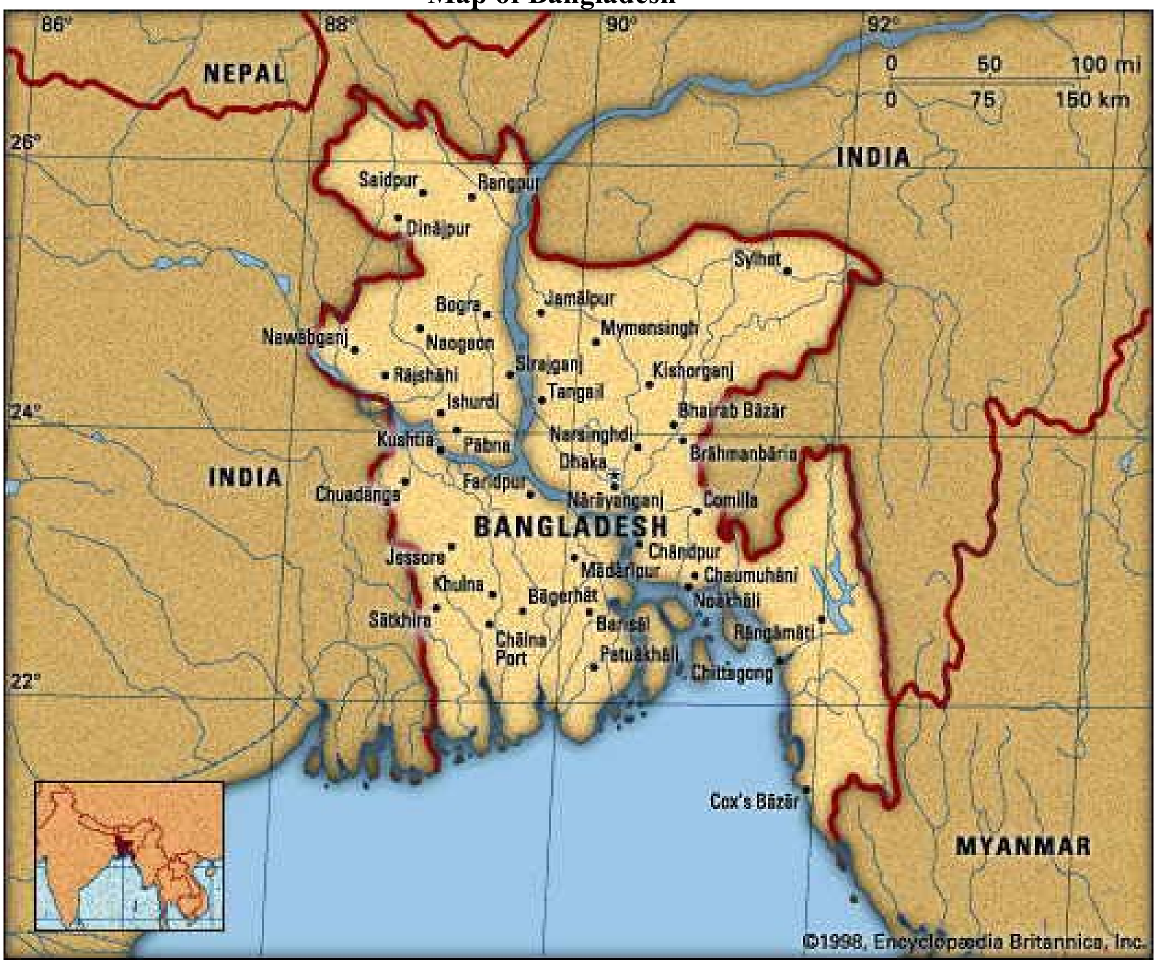
Energy Scenario of Bangladesh and the role of Solar and Wind Resources

1. Country profile of Bangladesh

Geographical Location : Between $20^0 34'$ and $26^0 38'$ North latitude, $88^0 01'$ and $92^0 41'$ East longitude.

Area : 147,570 sq, km

Map of Bangladesh



Land Type	: Consists mostly of flat fertile alluvial land.
Population (2006)	: 138.8 million
Population density	: 941 per km^2
No. of Household (2001)	: 25.40 million
Average Household(2001)	: 4.8 persons
Per capita GDP (2003)	: $389 (World per capita— $5,327)
Per capita GDP (2006)	: $456

2. Conventional Energy Supply and Resources

Energy consumption per capita in Bangladesh is extremely low compare to neighboring countries as shown in table below.

Table 1: Per capita energy consumption (kgoe, 2003).

Country/ Region	Energy Consumption	Country/ Region	Energy Consumption
1. Bangladesh	157	5. India	520
2. Nepal	355	6. China	1094
3. Sri Lanka	422	7. World	1688
4. Pakistan	467	8. OECD	4588

Source: IEA

The consumption per capita is half of even Nepal and $1/10^{th}$ of the world. A much higher consumption must be made to raise GDP and to alleviate poverty.

2.1. Biomass Energy:

The major part of energy consumed comes from biomass which is used mostly for cooking in rural areas and for rural industries. It forms 68% of total energy supply while 32% is supplied by commercial energy (including hydro power).

For most villagers cooking is a drudgery as due to shortages of fire wood biomass residues have to be collected and inefficient cookers employed produce unhealthy oxides and particulates. Improved biomass cookers would be of help but around 300,000 of them have been built for only 1.5% of 20 million rural households. The number of households having biogas digesters for cooking is a factor of 10 smaller at around 30,000. Presently 12 million tons of coal equivalent biomass is consumed in the industrial and domestic sectors along with commercial energy. Fire wood forms only 10% of the supply as shown below.

Table 2: Estimates of Energy Supplied by Traditional Biomass Fuels

('000' tons of coal equivalent)

Fuels	1999-00	2000-01	2001-02	2002-03	2003-04
Cow-dung	2441	2471	2471	2471	2502
Jute stick	922	966	1010	966	922
Rice straw	1375	1429	1409	1418	1218
Rice hulls	2810	2810	2854	2898	2854
Bagasse	314	340	366	366	392

Fire wood	1166	1166	1219	1219	1272
Twigs and Leaves	1325	1378	1431	1484	1537
Other wastes	1186	1230	1273	11317	1361
Total	**11539**	**11790**	**12033**	**12139**	**12258**

Source: BBS (Bangladesh Bureau of Statistics)

The consumption of biomass has remained stagnant over the years and there is little chance to produce a larger amount of biomass. However efficient biomass technologies can improve energy supply from biomass.

2.2. Electrical Energy:

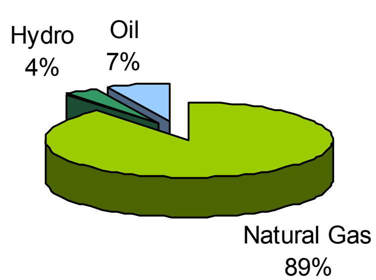
The availability of the most useful form of energy, electricity, is again extremely small as shown below.

Table 3: Electricity Generation and Consumption in Bangladesh, 2005-2006.

Item	Quantity
Installation capacity	5,275 MW
Average demand	4,300-4,500 MW
Average generation	3,200-3,300 MW
Per capita generation	167 kWh
Per capita consumption	136 kWh

Figure below presents the fossil fuel supply for electricity generation which shows that natural gas is the major energy source.

Fig. 1. Generation Pattern FY2004



Electricity consumption per capita is one of the lowest on earth- around 1/18th of world per capita (2429 KWh). Serious shortages in generation capacity led to load shedding on 223 days for the total duration of 951 hours in the year 2003. This situation further deteriorated with time and in 2006 the maximum load shedding approached 2000 MWh causing serious disruptions in the industrial production and in the society. The shortfall in generation which continues till today is mainly due to old inefficient generators requiring heavy maintenance.

According to the National Energy Policy the projected demand in 2005 of 5,720 MW will increase gradually to 11,794 MW by 2020 for low economic growth of 6% and for a higher growth rate of around 8% it should be 17580 MW. Small power plants may be added to produce 1000-1200 MW around 2006-2007 but the electricity crisis would continue as the demands will not be met.

2.3. Indigenous Fossil Fuels:

The recoverable proven and probable reserve of natural gas in 22 gas fields is 20.5 tcft (according to BBS) of which 6 tcft gas was produced by 2005 and 14.5 tcft (proven and probable) gas was left while the annual gas production is around 0.5 tcft in 2005. Proven amount would be much smaller. 46% of natural gas is consumed for electricity generation and fertilizer production uses 21% of the gas while other sectors consume the rest 33% as shown in table below.

Table 4: Production and Consumption of Natural Gas

Category/Year	2000-01	2001-02	2002-03	2003-04	2004-05
Gas Production: (10^9cft)	372.16	391.53	421.16	454.59	486.75
Consumption: (10^9cft)					
Electricity	175.27	190.03	190.54	199.40	211.02
Captive	0	0	0	32.03	37.87
Fertilizer	88.43	78.78	95.89	92.80	93.97
Industrial	47.99	53.56	63.76	46.49	51.68
Tea-garden	0.65	0.72	0.74	0.82	0.80
Brick field	0.44	0.53	0.52	0.12	0
Commercial	4.06	4.25	4.56	4.83	4.85
Domestic	31.85	36.74	44.80	49.22	52.49
C.N.G.	0	0	0.23	1.94	3.62
Total Consumption	348.69	364.61	401.04	427.65	456.30

Source: BBS

The gas consumption must increase to improve GDP. Table below presents Bangladesh fossil fuel reserves. We find that our gas reserve is around 1/250th while coal reserve is 1/5000th of world reserves. Per capita reserve of gas in Bangladesh is then around 1/5th and of coal 1/100th of world per capita. The situation is not happy at all for Bangladesh although some more gas and coal reserves are likely to be discovered in future. Fossil fuel reserves of Bangladesh are compared with world reserves in the table below.

Table 5: Fossil Fuel Reserves

Country/ World	Gas trillion cft	Oil million barrels	Coal million tons
Bangladesh	20	5.5	2295
World	5016	1,030,444	10,967,373

One million ton of coal is to be extracted per year from Barapukaria coal mine. This is equivalent to 0.03 tcft gas and should provide 240 MW generations by 2007. The following table shows the coal deposits discovered so far.

Phulbari deposit was planned to be mined by Asia Energy Corporation with its first production in 2008 and full production in 2013. However, the planned open pit extraction of coal could not be started due to the pressure inhabitants of the locality who would be dislocated from their homes and hearths and as serious environmental degradation might have occurred.

Table 6: Coal Deposits discovered in Bangladesh

Coal Fields	Depth of coal seams in meter	Reserves in million tons
Jamalganj, Bogra	640-1158	1053
Barapukaria,Dinajpur	118-506	303
Khalaspir,Rangpur	257-451	147
Dighipara,Dinajpur	250	200
Phulbari,Dinajpur	152-246	572

Source: Energy&Power, August 1, 2005 and May 1 2006.

2.4. Imported Fossil Fuels:

Bangladesh transport system depends almost totally on imported liquid fuels. Kerosene is used widely for lighting in villages while diesel generators are getting unavoitale. The amount of crude oil and petroleum products imported is shown below.

Table 7: Import of Petroleum Products and Crude Oil

Year	Crude Oil		Petroleum Products	
	Oty Thousand tons	Value Million US$	Oty Thousand tons	Value Million US$
2001-02	1225	220	2072	2536
2002-03	1331	289	2214	3319
2003-4	1252	314	2262	4015
2004-5	1063	364	2692	7214

Bangladesh Orthornaitic Samikhha, Ortho Mantranalay, 2006

The cost of import is soaring high and becoming prohibitive. Use of less polluting local CNG should be popularized. Bio-fuel using indigenous plants presents a possibility which should reduce petroleum imports. Pollution too would be less.

Again, a small amount of coal, around 0.1 million ton, is imported annually. The imports require hard earned foreign exchange and have to be kept limited. Import of electricity from Nepal through international funding for hydro generation is too remote a possibility and would be subject to international vagaries.

Natural gas reserves in Bangladesh are likely to be depleted before 2020 and electricity production from gas may stop. Coal may supply 250 MW from Barapukaria deposits. As the demands would be over 11000MW serious attempts have to be made for energy conservation and for high energy efficiency along with explorations for gas and coal reserves to avert an impending disaster from shortage of energy supply. But more importantly energy supplies using RETs must be developed and utilized.

Fuel imports must be kept limited. A larger dependence on imported fuel would mean absence of energy security for the country which must be avoided.

3. New Technologies

Pollution free fusion reactors are still a fantasy and so far Bangladesh could not arrange electricity production from fission reactors. France is expected to take a leading role in building one experimental thermonuclear fusion reactor by 2015. If economically successful Bangladesh may look forward to nuclear reactors for generation of electricity without risks from nuclear fallout. But this is a remote possibility. However, Bangladesh may well go for installing nuclear reactors at Ruppur for 1000-2000 MW as the risks associated with modern reactor technology are likely to be lower than the risks from power shortage.

Government of Bangladesh has declared its vision to provide electricity for all by the year 2020. To fulfill the (Government of Bangladesh's) GOB's objectives of electrification, utilization of renewable energy technologies must play a vital role for off-grid electrification. The supply of electricity to the grid using RETs has to be attempted. Grid connected PV is now progressing fast in Germany and Japan. Bangladesh has a better solar resource and a larger amount of electricity would be generated here from the same solar panel.

At present, the share of Renewable Energy Technologies (RETs) in electricity production is very low. Conventional hydro produces 4% of electricity. New technologies for solar and wind contribute only 0.1% at the time. However, the potentiality of RETs is recognized by all and the Power Cell of the Ministry of Energy and Mineral Resources has produced a draft Renewable Energy Policy which is yet to be accepted by the government for its implementation. The target proposed is to generate power utilizing new renewable technologies to share 5% of total electricity demand by 2010 and 10% by 2020. Attempts to attain the targets should not be delayed any further.

RETs which have found wide scale used in Bangladesh are shown in the following table.

Table 8: Wide scale use of RETs

No.	Technology	Number of units
1.	Solar home system	above 100,000
2.	Improved biomass cooker	around 300,000
3.	Biogas plants	around 25,000
4.	Biomass bracketing machines	around 100

Major players have been NGOs like Grameen Shakti and BRAC as well as BCSIR.

Life size demonstrations have been on for many RETs. A number of organizations are involved including LGED, RERC, BUET, BAU, REB, BPDB, BCSIR, BRAC, GS, CMES and Rahimafrooz Ltd in technologies such as:

1. Solar Water Heaters
2. Solar Dryers
3. Solar Cookers
4. Water Lifting Wind Turbine
5. Wind Electricity Generators
6. Hybrid Generators- solar/wind/diesel
7. Grid Connected Wind Turbine
8. Micro Hydro Generator
9. LED lamps

The demonstrations have proved to be generally attractive but large scale deployment of the technologies are yet to be made.

It may be mentioned that

1. BPDB has floated a tender for installation of a wind battery power plant of 1MW capacity
2. IDCOL has invited proposals for developing a 1-2MW solar panel assembly plant

4. Barriers to greater utilization of Renewable Energy Technologies

There are plenty of barriers hindering widespread deployment of potential RETs in Bangladesh. Different types of barriers experienced are discussed in the subsequent headings.

1. Information Barriers

- Lack of information among the public and policy makers about renewable energy resources, technical/economic information about RETs.

2. Policy Barriers

- Absence of a national renewable energy policy, programs and goals although a draft policy has been prepared by the Power Cell, Ministry of Energy and Mineral Resources (MEMR).

3. **Institutional Barriers**
   - Absence of a dedicated national agency like Renewable Energy Development Authority (REDA) or Sustainable Energy Development Authority (SEDA) to plan, co-ordinate and finance.
4. **Technical Barriers**
   - Local manufacturing and/or assembly of renewable energy technology components and equipment are currently limited.
5. **Market Barriers**
   - The high upfront cost at the end user level for renewable energy is a major barrier.
6. **Economic, Financial and Financing Barriers**
   - Lack of appropriate financing mechanisms for renewable energy except for SHS.
7. **Human Resource Barriers**
   - Limited expertise on system design, installation, operation and maintenance of renewable energy technologies and on project development.

It is learnt that Sustainable Energy Development Authority (SEDA) to look after renewable energies, energy efficiency and energy conservation may be established. Such a move should help remove the barriers prevailing in the renewable energy sector provided appropriate actions are taken by SEDA.

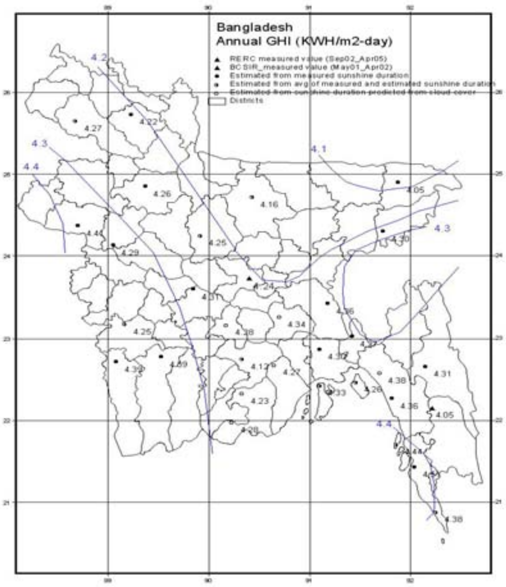
A major step in addressing the Information Barrier for wind and solar energy has been taken. A fair amount of detailed and precise information on solar and wind energy is now available through the UNEP's (United Nations Environment Programme) SWERA (Solar and Wind Energy Resource Assessment) program with RERC as the country partner for Bangladesh. SWERA toolkit (website) offers information to all. Some of the results of the assessments made by RERC together with NREL (National Renewable Energy Laboratory) of USA, DLR (German Aerospace Center) of Germany and RISOE (Risø National Laboratory) of Denmark are presented below.

5. Solar and Wind Resource Assessment

5.1. Solar Resource:

Global and diffuse radiation measurements at RERC, Dhaka University kept suspended for a decade were restarted in 2002 as part of SWERA Program. The activities have been continuing since then. Eppley pyranometers with a computer interfacing card and a micro computer have been employed. Data are measured every minute and integrated values over an hour are used to obtain hourly, monthly and annual values. Calibrations with a new pyrheliometer and a new K&Z pyranometer are occasionally made. To estimate radiation values over Bangladesh sunshine duration and cloud cover measured by Bangladesh Meteorological Department at 31 stations are used employing correlations developed at RERC. Annual values of Global Horizontal Insolation obtained is shown below.

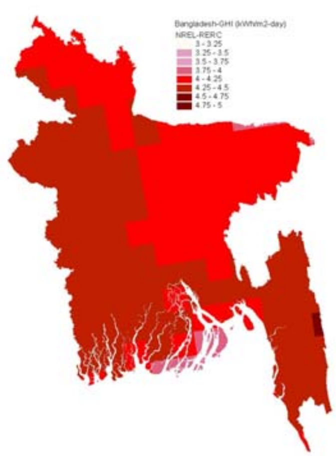
Fig. 2: Annual values of Global Horizontal Insolation (GHI) for 31 locations in Bangladesh)



The whole area of Bangladesh has been covered by independent assessments of NREL using the CSR (Climatological Solar Radiation) model which utilized information on cloud cover water vapour trace gases and aerosols over the years 1985-’91 and produced a 40×40 km resolution map. Their annual map has been tuned to Dhaka pyranometer data and the tuned GHI (Global Horizontal Insolation) map of NREL is shown below.

Fig.3 : GHI map of NREL tuned to Dhaka

Fig. 4: GHI map of DLR tuned to Dhaka



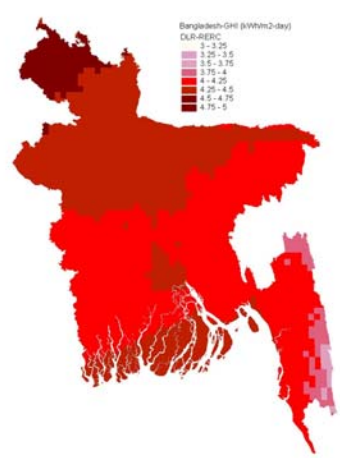
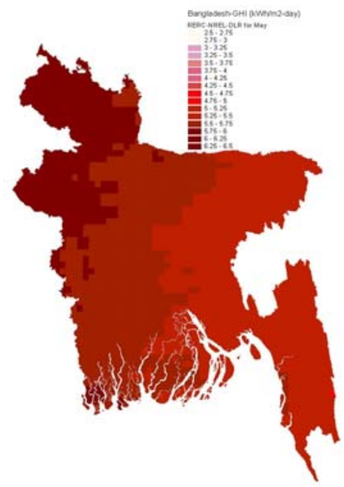


Fig. 5: GHI map of RERC-NREL-DLR showing averaged NREL and DLR tuned maps

Fig.6: GHI map of RERC-NREL-DLR for a typical month, May



Based on satellite data collected in the years 2000, 2002 and 2003 DLR Laboratories in Germany has produced 10km×10km resolution monthly and annual maps. Their maps have been tuned to Dhaka data and the annual map is presented above. It may be mentioned that variations between maps of NREL and DLR are not large and GHI values are within 2%.

Monthly and annual maps have also been prepared for diffuse and direct normal radiation. The SWERA archive contents valuable data for locations all over the country.

5.2. Wind Resources

In Bangladesh, adequate information on the wind speed over the country and particularly on wind speeds at hub heights of wind machines is not available. A previous study (1986) showed that for the wind monitoring stations of Bangladesh Meteorological Department (BMD) the wind speed is found to be low near the ground level at heights of around 10 meter. Chittagong – Cox's Bazar seacoast and coastal off-shore islands appeared to have better wind speeds. Measurements at 20m and 30m heights have been made later on by BCAS, GTZ and BCSIR. WERM project of LGED for measurements at the height of 20 and 30m have been going on for 20 locations all over Bangladesh.

However, the speed at a higher height of 50m which is often used for wind generators has not been available. This SWERA Programme provides predictions for wind speed and wind energy density at different heights including 50m height to look for the possibility of wind power generation.

For prediction of wind speed at different heights and for assessment of wind energy in the coastal part of Bangladesh, Wind Atlas Analysis and Application Program (WAsP), a micro-scale modeling software has been used. WAsP develops models for obstacles, roughness and terrain surrounding a measuring station and then generates a regional wind climate or a wind atlas for the region around $100km^2$ in area.

As a case study Figure 1 shows (a) a digitized map of Kutubdia Island showing variations in roughness where two wind monitoring stations of BMD and BCAS have been located and (b) models for obstacles at BCAS and BMD locations. For BMD location effects of obstacles are very high due to a cyclone shelter building and lots of trees close to the met station.

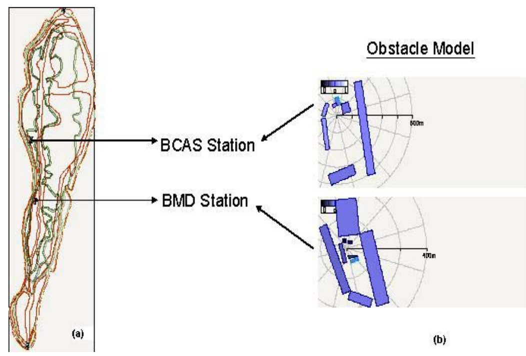


Fig.7 : (a) Digitized map of Kutubdia (b) Obstacles model in WAsP

After analyzing all the effects, the monthly and annual wind atlas for locations all over Kutubdia Island have been developed using 10 years (1991 – 2000) of three hourly time series data of BMD and one year (Sept96-Aug97) data of 10 minute time series data of BCAS. The developed wind atlas was used to find out locations with high wind speeds by generating the wind resource map with the help of (100 x 100) m^2 grid cells as shown in the figure below.

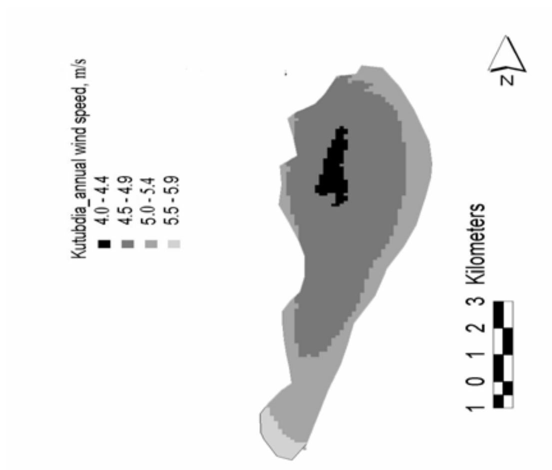


Fig. 8: Wind resource map for 50m height above the ground level over Kutubdia Island

The developed wind atlas of four coastal locations of Bangladesh, Charfassan, Chittagong, Kutbdia and Cox`s Bazar using one year data of BCAS shows that at 50m height for the roughness value from 0m (open sea, water areas) to 0.03m (farm land with very few buildings, trees, airport areas etc) the wind speed varies from 4.1 to 5.8 m/s with a power density of 100 - 250 w/m^2.

BCAS time series data on wind speed and direction at 25m height have been employed using WAsP techniques to obtain predictions of wind speed and power density at 50m around the stations at Kuakata, Patenga, Charfassion, Kutubdia and Cox'sBazar. The power densities obtained are 154, 133, 164, 184 and 117 W/m^2 respectively. The predicted wind speed at 50m height is shown in the table below for BCAS, GTZ and BCSIR data for 11 locations. A speed dependent power law (2002) developed using Indian data for coastal stations with the index α.

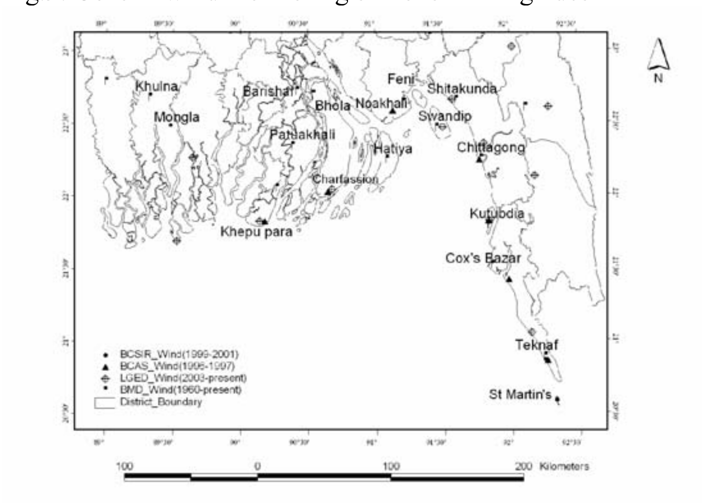
$$\alpha = 0.43e^{-0.19V}$$

predicts less accurate but a simpler method using only monthly values of wind speed. The predicted wind speed at 50m height for a number of coastal locations in Bangladesh are shown below.

Table 9: Wind Speed at Coastal Locations in Bangladesh (m/s)

Location	WAsP	Exponential Fit
Kuakata	4.8	5.1
Patenga	4.7	4.4
Charfassion	4.7	4.5
Kutubdia	5.3	4.8
Cox's Bazar	4.3	3.7
Noakhali	-	3.4
Teknaf 1	-	3.3
Feni	-	5.1
Anwara	-	4.6
Teknaf 2	-	5.0
St. Martin	-	5.0

Fig.9: Coastal wind monitoring stations in Bangladesh



From detailed assessments it has been found that the wind speed in the coastal areas goes up to 5.8m/s. But as there is a strong seasonal and diurnal variation in Bangladesh wind power density is higher than for most locations having the same annual wind speed. It may be noted that some of the locations have wind power density above 150 W/m^2 and there should be a good potential for wind generation.

Wind resource assessment over Bangladesh has been done independently by RISOE National Loboratory, Denmark using KAMM (Karlsruhe Atmospheric Meso-scale) model. The model uses upper atmosphere wind speed data and satellite information. Based on a comparison between KAMM (done by RISOE) and WAsP results (done by RERC) the wind resource map for Bangladesh has been developed and added to SWERA archives.

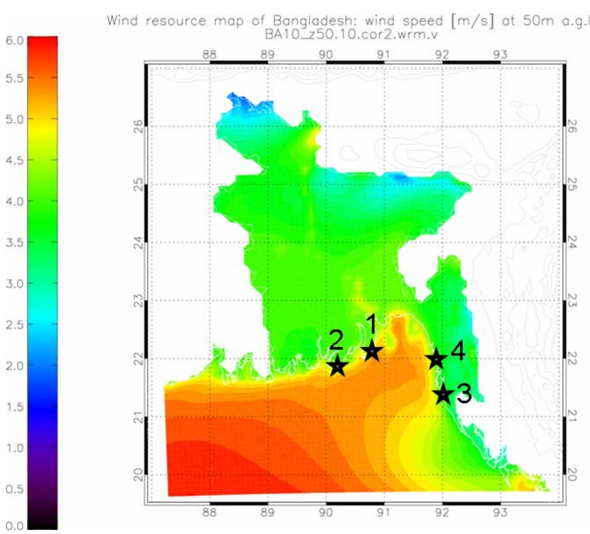


Fig.10. The wind climate of Banglaadesh at 50m above ground level along with BCAS stations.

Wind energy density predicted by RISOE show locations with power density above 200W/m^2 over 2000km^2 which is highly encouraging. This has to be established from experimental measurements to go for large scale applications of wind energy.

6. Applications of SWERA Products

The solar and Wind Energy Resources Assessment (SWERA) project has produced data and maps for global, diffuse and direct normal radiation and the radiation availability on collectors tilted at latitude angles for locations all over Bangladesh. Wind maps have been developed for the whole of Bangladesh and wind atlas has been produced for several cases. These should help applications of solar and wind energy in the country.

The availability of global radiation is in the range from 4.0- 4.5 kWh/m^2/day. The total yearly amount of solar radiation arriving over the surface of Bangladesh is then at least 2.4×10^{14} kWh while the present electricity generation is 2.0×10^{10} kWh. Hence the solar radiation available is 10,000 times electricity generation. If 1/1000 part of Bangladesh is used for electricity generation from the sun with only 10% efficiency we can generate the same amount of electricity as produced by all the conventional resources. Again, solar thermal flat plate collectors have efficiency usually between 30 and 50% and a large amount of thermal energy generation may be made.

In rural areas where grid extensions are economically or technically prohibitive single Solar Home Systems (SHS) has already been providing electrical lights for over 100,000 households through SHS. this has been possible due to laudable activities of NGOs with financial support from IDCOL. This annually displaces around 18 million litres of kerosene. Since kerosene is imported in Bangladesh; any reduction in their consumption help lower foreign exchange outgo besides making the country that much more secure in terms of energy supply. Again, GHG emission would be lowered. Solar radiation availability is high all over Bangladesh and PV should play a vital role in providing electricity to all in rural Bangladesh.

BPDB uses millions of litres of diesel to generate around 250×10^3 MWh of electricity every year. Again, diesel is consumed in large quantities for rural markets and homes and for irrigation water pumping or as an auxiliary resource for urban areas. Reduction of diesel consumption by renewable resources would help lower import cost and lessen GHG emission and attempts ought to be made to apply solar and wind resources.

From RETScreen (Renewable Energy Technology Screen) and HOMER (Hybrid Optimization Model for Electric Renewables) computer programs it is found that hybrid generation using PV or wind along with diesel is cost effective for Bangladesh for many locations. Hence for remote and rural locations hybrid generation ought to start. A case study for cost of generation is shown in table 10.

Table 10: Cost comparison for different modes of generation

Power Generated	Location	Wind speed	Generation Mode	Cost/kWh (Taka)
100 kW	Kuakata	5.5 m/s	Diesel only	29.7
		5.5 m/s	Wind-Diesel	16.3
		5.5 m/s	PV-Wind-Diesel	16.8
		5.5 m/s	PV-Wind	19.8
		5.5 m/s	Wind	24.4

For solar water heaters the payback period is around 4 years hence use of water heaters in hospitals, hotels and industries would reduce electricity load and GHG emission. If measurement supports prediction of RISOE of excellent potential of wind over 200 km^2

large wind generators should be feasible. Again, grid connected PV should be attractive when solar cell prices fall down and diesel prices go up and 10-20% grid generation may be effected by solar PV.

8. Environmental Issues

Green house gases (CO_2, CH_4, N_2O) emitted in burning of different types of fuels lead to global warming. GHG emission factors which are mostly due to CO_2 are shown below.

Table 11: GHG emission factor

Item	GHG emission factor
Kerosene	2.5 ton CO_2/ton
Wood/straw	1.73ton CO_2/ton
Diesel genset (η=21%)	1.3 ton CO_2/MWh
Diesel (η=30%)	0.897 ton CO_2/MWh
Bangladesh grid (natural gas 90%)	0.452 ton CO_2/MWh
Natural gas	0.452 ton CO_2/MWh
Hydro, Solar, Wind	0

We find that GHG emission from electricity grid (20,062MKWh) is 9 million tons. This scenario for CO_2 emission energy production in Bangladesh as given by IEA for 2003 is shown below.

Energy-Related Carbon Dioxide Emissions: 32.9 million tons
Per Capita Energy Consumption: 4.0 million Btu
Per Capita Carbon Dioxide Emissions: 0.23 tons

The demand of electricity, the major option of energy, is increasing day by day; therefore energy related GHG emission is also increasing. CO_2 emission from electricity generation should increase by a factor of 3 or so by 2020 from the present value of 9 million tons and the total CO_2 emission should be at least 50 million tons. This increase in the amount of CO_2 in the atmosphere of the earth is not desirable. Internationally attempts are being taken to decrease GHG emission and Bangladesh should try to help the effort. Again if GHG emission is reduced Bangladesh may earn $5 or so for each ton of reduction through carbon trading. For 10% reduction of CO_2 Bangladesh would earn around 50 million dollars or so. Efforts for GHG mitigation should start immediately.

According to the Power Cell of the Government of Bangladesh the tentative target for renewable energy utilization by 2020 is shown below along with estimates for GHG reduction.

Table 12: Power Cell targets for RETs

Tentative Target for RETs, 2020 and GHG reduction

Resource	Expected utilization	GHG reduction (million tons of CO_2)
Wind	1000 MW	5.0
Solar	300 MW	0.5
Biomass/Hydro	600 MW	0.6
Co-generation	300 MW	0.3
Total Renewable Energy	3200 MW	6.4

9. GHG (Green House Gas) mitigation:

From RETScreen (Renewable Energy Technology Screen) analysis the following results for CO_2 reduction have been found for various proposed applications of RETs.

Table 13: Potential for electricity generation from Solar and Wind energy technologies and the scope of CO_2 mitigation by 2020

	RET	Indicative Potential	In place of conventional generation using	CO_2 reduction potential ($MtCO_2$/year)
1	Hydro electricity (existing 230MW)	300MW	Grid	1.4
2	Solar Home Systems	50W, 2 million	Kerosene & Grid	1.5
3	Solar lights for the poor	10W, 2 million	Kerosene	0.6
4	Wind Diesel hybrid microgrids	100kW, 300	Diesel genset	0.1
5	PV Diesel hybrid microgrids	100kW,300	Diesel genset	0.1
6	Wind electricity generation(minimum)	200MW	Diesel genset	2.1
7	Grid connected PV(if grid is statble)	200MW	Grid	0.8
			Total=	6.6

Table 14: Potential of thermal energy from Solar and the corresponding scope for CO_2 mitigation by 2020

	RET	Application of RET	CO_2 reduction potential ($MtCO_2$/year)
1	Solar Water Heaters	1 sq. Km Panel utilization	0.4 (by replacing Grid)
2	Improved biomass cookers (15% more efficient than conventional) and biogas digesters	1 million ton Biomass replacement	1.9
		Total=	2.3

Notes: Wood/straw produces 3.8 ton CO_2 / ton fuel

We find that CO_2 mitigation for our proposed applications are similar to the targets of Power Cell.

10. Recommendations to strengthen RET programs

- Ongoing SHS program should be strengthened to enable installation of 500,000 units by 2020
- The program for biogas project and biomass cooking stove should be strengthened.
- Measurement of Global radiation started less than a year back at seven locations must continue together with GHI, DIF and DNI measurement at RERC Dhaka.
- RISOE may produce 1km×1km resolution map for coastal belt
- WAsP studies should be made for LGED wind stations
- Feasibility studies should start on:
    a) Solar water heating in hospitals, rural health centers, hotels and industries
    b) Hybrid electricity generation using wind/PV/diesel
    c) Biomass gasifiers particularly using rice husk
    d) Grid connected PV
    e) Production of biofuels using Jatropha and similar plants

Funds for the above projects have to made available along with additional resources for innovative activities on RETs. Bangladesh faces a challenge to supply energy for development and the challenge has to be accepted squarely. Due to limited fossil fuel reserves of Bangladesh the country should rely on inexhaustible renewable energy resources. RETs along with technologies for energy conservation and energy efficiency can help over come energy shortages and lead the country to progress provided necessary steps are taken now without delays.

Conclusion:

The SWERA activities show that for all locations of Bangladesh solar radiation availability is excellent. The diffuse component is around 50% and non-concentrating PV or thermal collectors should be most suitable for use. For coastal Bangladesh the measured wind speed is high in monsoon months and wind generators with hybrid generation for other months have a good potential. Estimates by RISOE from upper atmosphere data show high enough wind speeds for large wind generators over 2000km^2. RETs along with conservation and efficient utilization of fossil fuels should allow the country to progress in the next decades when gas reserves get depleted. Large scale utilization of solar and wind energy should help energy security in the face of impending energy crisis from dearth of conventional energy supply. The challenge to develop and utilize RETs must be accepted boldly.

Reference materials :

1. Bangladesh Power Development Board, http://www.bpdb.gov.bd
2. Statistical Pocketbook of Bangladesh, 2003
3. Local Government Engineering Department, http://www.lged-rein.org
4. Grameen Shakti, http://www.grameen-info.org/grameen/gshakti/
5. 1st grid connected wind energy project in Bangladesh, M Fazlur Rahman, Energy & Power, vol-3(1)
6. Infrastructure Development Company Limited, http://www.idcol.org
7. World Bank, “Market Assessment Survey of Solar PV Application in Bangladesh, Final Report, Dhaka, Bangladesh, July 1998
8. World Bank, “Feasibility Study for a Solar Home Systems Project within the Context of
Alternative Options for Rural Electrification, Final Report, Dhaka, Bangladesh, 2000.
9. SWERA website: http://www.swera.unep.net
10. A study of the wind speed and wind energy availibility in Bangladesh, M. Hussain, S. Alam, K.A. Reza and M. Sarker, Energy Conv. and Magnt. Vol. 26 (1986), pp.321-327.
11. Dependence of power law index on surface wind speed, M. Hussain, Energy Conv. and Magnt. vol.43 (2002), pp. 467-472.

Section 2
ASSESSMENT OF BANGLADESH SOLAR RESOURCE

1. Solar radiation Measurement

Renewable Energy Research Centre (RERC), Dhaka University has been measuring Global Horizontal Irradiance (GHI) since September 2002 under the SWERA program. It has been collecting hourly data at one minute intervals using an Eppley Precision Pyranometer and ICP-CON data acquisition card with a microcomputer. Measurement of Diffuse Irradiance (DIF) has been going using another Eppley Precision Pyranometer with a manually adjusted tracking shadow ring. Both the Pyranometers are placed on roof of a two storied building having fine surrounding aperture. 2 channels of the same data acquisition card are used for GHI and DIF data. RERC has been using an Eppley Normal Incidence Pyrheliometer occasionally for instantaneous measurement of Direct Normal Irradiance (DNI) for clear sky conditions. Sunshine duration measurement has been going on since March 2003 with a Campbell-Stokes sunshine recorder (courtesy of Bangladesh Meteorological Department).

Bangladesh Council of Scientific and Industrial Research (BCSIR) measured Global Horizontal Irradiance at Dhaka and Bandarban for about a year only using automatic data recording system. Bangladesh Meteorological Department (BMD) has started GHI measurement using Eppley Precision Pyranometer for 7 stations over the country. For automatic recording K&Z Data Loggers have been arranged under SWERA programme using international funding.

2. Calibration and Screening of RERC data

Global radiation is composed of the directly coming solar radiation and of the diffuse radiation itself. The fraction of diffuse radiation which is obstructed by the surrounding obstacles (inclined $> 5^0$) has been added with the measured GHI values. From a study of the surrounding obstructions it was found that 2% area of the hemisphere is obstructed.

Diffuse radiation is obstructed from receiving the pyranometer due to the shadow ring used for the measurement and by the surrounding obstacles like trees or buildings. To get reliable diffuse radiation values necessary correction factors have been introduced.

Calibration has been done often. For this purpose RERC has been using a new K&Z Pyranometer, a new Pyrheliomer and two hand held data loggers.

Frequently the pyranometer were cheeked. A few data were screened due to 1) misalignments of the shadow ring, 2) misbehavior of the background or offset values and 3) dirtying of the glass surface from bird's waste.

Measured GHI and DIF data for each minute were averaged to get monthly averaged data. For January 2003 to December 2005 monthly averaged GHI and DIF values are given in Table 1 in the next page.

Table 1: Monthly averaged hourly GHI (Wh/m^2)

Hours/month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5:30			1	5	17	19	11	7	3			
6:30	3	8	29	66	106	93	86	66	58	46	31	11
7:30	57	93	148	198	252	200	198	180	165	169	157	97
8:30	175	254	318	354	406	321	355	288	303	324	331	237
9:30	300	424	489	521	561	416	438	433	435	473	490	382
10:30	411	573	629	666	681	494	503	514	485	487	580	479
11:30	494	672	712	751	727	532	548	537	485	520	614	498
12:30	518	701	722	764	711	543	570	535	486	488	573	489
13:30	483	646	657	693	641	500	503	482	441	406	510	426
14:30	379	528	541	553	577	451	463	453	385	323	377	309
15:30	236	353	377	402	419	329	372	356	281	208	204	183
16:30	94	175	204	237	257	215	244	231	164	76	57	54
17:30	10	37	55	72	93	93	107	89	45	6	1	2
18:30			2	4	11	17	18	8	1			
Daily average (kWh/m^2-day)	3.16	4.46	4.88	5.28	5.46	4.22	4.42	4.18	3.74	3.53	3.92	3.17

Note: 5:30 represents the period between 5am to 6am

Table 2: Monthly averaged hourly DIF (Wh/m^2)

Hour/Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5:30			1	5	16	18	11	6	3			
6:30	3	7	27	58	90	80	70	58	55	37	23	10
7:30	47	70	109	147	183	156	145	140	137	108	87	59
8:30	117	146	189	238	253	228	226	217	229	172	137	109
9:30	172	205	244	308	322	281	287	292	279	238	176	145
10:30	220	250	281	350	356	325	318	343	327	248	205	171
11:30	250	274	297	372	381	339	349	350	333	263	223	194
12:30	257	264	306	367	375	348	356	342	304	268	217	208
13:30	240	254	276	339	345	317	295	319	269	219	206	193
14:30	199	221	245	284	303	282	250	270	259	173	167	156
15:30	139	170	191	217	238	215	211	224	187	122	110	105
16:30	69	104	127	151	164	152	149	157	115	55	43	40
17:30	9	30	46	60	77	75	82	68	38	5	1	2
18:30			1	4	12	15	16	7	1			
Daily average (kWh/m^2-day)	1.72	1.99	2.34	2.90	3.12	2.83	2.76	2.79	2.54	1.91	1.60	1.39

3. Estimation of GHI

Solar radiation data are necessary to design and set up of solar devices, but in the developing countries the number of solar radiation measuring stations is not large. Prediction of solar radiation may be done using meteorological parameters as most of the paramereters are correlated in nature.

Angstrom developed a correlation equation between the solar radiation and sunshine duration as

$$\frac{\overline{H}}{\overline{H}_o} = a + b\frac{\overline{n}}{\overline{N}}$$

$\overline{H}/\overline{H}_o$ is the ratio of monthly averaged daily GHI to monthly averaged daily extraterrestrial radiation on a horizontal surface, $\overline{n}/\overline{N}$ is the ratio of monthly averaged daily sunshine hours to monthly averaged day length hours and a, b are correlation coefficients.

Using the measured sunshine duration and global radiation data at RERC, Dhaka University for September 2002 to April 2005 Angstrom correlation is followed. It has been found that better correlations are obtained if biannual fits with March to September (summer) in one group and October to February (winter) in another group are made in place of annual fit of data. The fits are shown in the following graphs along with R^2 values.

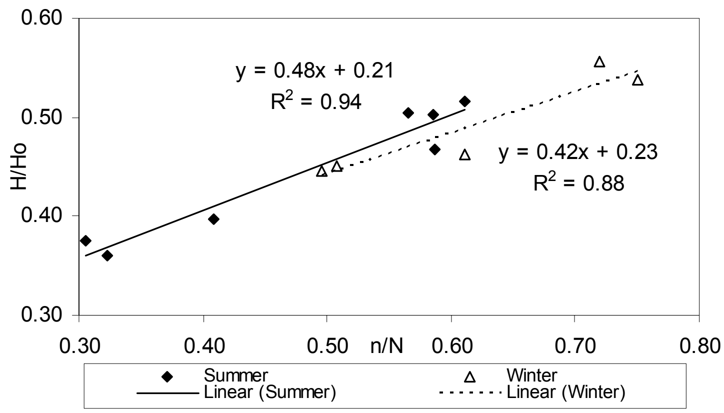


Figure 1: Correlation between monthly $\overline{n}/\overline{N}$ and $\overline{H}/\overline{H}_o$

For estimation of GHI the annual rms error is 0.15kWh/m2-day and the percentage error is 3.5%.

Cloud cover is a direct specifier of sunshine duration and they are correlated. An increase in cloud cover shows a decrease in sunshine duration. Utilizing this correlated nature, if sunshine duration data are not available or if sunshine duration data are not satisfactory for some locations, cloud cover data is useful to predict sunshine duration for those locations.

Estimation of sunshine duration from cloud cover data has been done using the state of the sky technique of Barbaro et. al.. The relative sunshine duration and state of the sky are related by the following equation-

$$\frac{n}{N'} = \frac{an_1 + bn_2 + cn_3}{n_{123}}$$

Where, n_1 is the number of clear days, n_2 is the number of mixed days, n_3 is the number of overcast days in a month, $n_{123} = n_1 + n_2 + n_3$ is the total number of days in the month under consideration; a, b, c are climatological parameters and N' is the period when the

Campbell-Stokes sunshine recorder remains sensitive over the representative day for the month and $N' = \frac{\arccos\left(\frac{\cos 85 - \sin\phi \sin\delta}{\cos\phi \cos\delta}\right)}{7.5}$, ϕ is the latitude of the station and δ is the declination.

The number of clear, mixed and overcast days in a month were determined according to table 3 following Barbaro.

Table 3: Classification of the days of a month

Cloud cover amount (in Octa)	Type of day
0-2	Clear day
2-4	Mixed day
4-8	Overcast day

The correlation has been applied for 1992-2003 data, by grouping sunshine duration and cloud cover measuring stations according to their annual rainfall. Annual rainfall of ≥ 2500 mm has been considered as the criterion for high rainfall stations and <2500mm annual rainfall for low rainfall stations. The parameters for sunshine duration and cloud cover data of 1992-2003, are given in Table 4.

Table 4: The climatological parameters and standard deviations of n

Station's rainfall status	Oct-Apr	May	Jun	Jul	Aug	Sep	Std. dev. of n (Hours)
	Values of c						
High rainfall a=0.9, b=0.7	0.5	0.42	0.32	0.3	0.35	0.45	0.35
Low rainfall a=0.85, b=0.7	0.5	0.5	0.35	0.32	0.37	0.4	0.29

For estimation of sunshine duration from cloud cover the annual average rms error is 0.32 hours/day and percentage error is 5%. This will lead to an additional error of 2% in GHI estimation.

Bangladesh Meteorological Department (BMD) has 31 sunshine duration and cloud cover measuring stations. For all the stations the yearly variations of sunshine duration and cloud cover have been studied as they are correlated. For most of the stations these variations are satisfactory but for a few are not may be due to the placement of the sunshine recorders on the ground level, for the shading or for unsatisfactory alignment of sunshine recorder. For these stations having unsatisfactory sunshine duration data estimations, average of the estimated and measured values were calculated from cloud cover data. For all these stations GHI values were calculated from sunshine duration for 1999-2003. The values of the sunshine duration and GHI have been placed on two Bangladesh maps and are shown in the following figures.

Figure 2: Annual sunshine duration available at BMD measuring stations

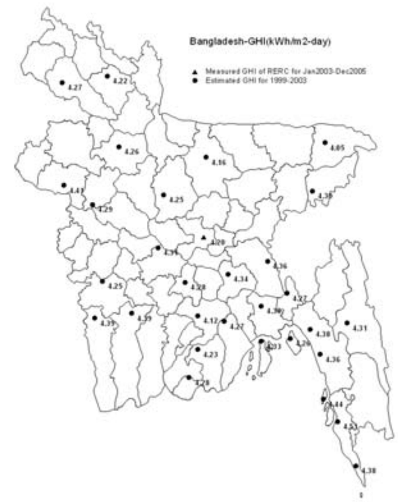


Figure 3: Annual Measured and Estimated GHI at RERC and BMD stations

4. Validation of GHI estimation technique

The correlation parameters have been employed for global radiation estimation at Bogra, Chuadanga, Rangamati and Satkhira stations for few months, for which daily sunshine duration and global radiation data are available.

For all the measured values available out of Dhaka gave a rms error of 0.4 kWh/m^2-day and 4% annual error for estimation. Typical monthly values are given in Table 5.

Table 5. Measured and estimated values of GHI for a few stations outside Dhaka

Years	Months	Station name							
		Satkhira		Bogra		Chuadanga		Rangamati	
		Meas.	Est.	Meas.	Est.	Meas.	Est.	Meas.	Est.
2005	Jan	3.31	3.33	2.91	3.14	3.08	3.22	4.09	3.78
	Feb	4.43	4.43	4.14	4.38	4.39	4.44	4.63	4.68

5. Model computations of GHI and maps

1. National Renewable Energy Laboratory (NREL), USA

National Renewable Energy Laboratory (NREL), USA developed a Climatological Solar Radiation (CSR) Model (SWERA website, http://swera.unep.net) for Bangladesh to provide monthly averaged daily total solar resource (kWh/m^2) averaged over surface cells of approximately 40 km× 40 km in size. CSR model used information on cloud cover, atmospheric water vapor, trace gases as well as the amount of aerosols in the atmosphere and NREL calculated monthly averaged daily total insolation for January 1985 to December 1991. The modeled values are accurate to approximately 10% of a true measured value within the grid cell. The local cloud cover can vary significantly even within a single grid cell as a result of terrain effects and other microclimate influences. Furthermore, the uncertainty of the model estimates increase with distance from reliable measurement stations and with the complexity of the terrain.

2. German Aerospace Center (DLR), Germany

The high resolution (10km×10km surface cell)) solar radiation assessment of DLR is based on data of a geostationary satellite, Meteosat 5 (M-5). M-5 has its position at 0° latitude and 63° East longitude. This satellite scans the specific area every 30 minutes with a spatial resolution of 5km×5km.

This model takes into account information about the clouds, data of the most important atmospheric components that attenuate the radiation are ozone, water vapor and aerosols. The calculation is based on the method of Perez et al (2002) and Ineichen and Perez (2002) (SWERA website). DLR calculated solar radiation values for the years 2000, 2002 and 2003 over the country. 3 annual and 36 monthly averaged daily total sums of GHI and DNI were prepared for each 10km×10km georeferenced pixel. DLR has also prepared hourly time series for several 10 sites.

The complete database (ESRI Shapefile and MS-Access database) can be downloaded from the SWERA-homepage.

Table 6: Sites for which times series data are available

Stations/Sites	Lat (degree)	Long (degree)	Elevation (m)
Barisal	22.75	90.33	2
Bogra	24.85	89.37	18
Chittagong	22.27	91.82	6
Cox's Bazar	21.43	91.93	4
Dhaka	23.77	90.38	7
Rajshahi	24.37	88.70	20
Rangamati	22.53	92.20	69
Rangpur	22.73	92.23	33
Satkhira	25.72	89.08	4
Sylhet	22.90	89.88	34

6. Model and Measured GHI values

Measured values for RERC and computed values of GHI are shown in Table 7.

Table 7: NREL, DLR and RERC values of GHI for Dhaka

	Radiative Transfer Models		Measured data		
Month	NREL (1985-'91)	DLR (2000,'02,'03)	1987-89 RERC	1992 RERC	2003-'05 SWERA/RERC
Jan	4.18	4.58	4.29	3.34	3.16
Feb	4.68	4.81	4.86	4.05	4.46
Mar	5.55	5.31	5.53	5.24	4.88
Apr	5.65	5.84	5.23	6.02	5.28
May	5.58	5.21	5.67	5.76	5.46
Jun	4.48	3.85	5.13	5.39	4.22
Jul	3.90	3.76	3.87	4.2	4.48
Aug	4.12	4.11	3.92	4.87	4.12
Sep	3.96	3.76	4.5	5.38	3.78
Oct	4.70	4.19	4.61	4.93	3.57
Nov	4.25	4.47	4.22	3.72	3.92
Dec	4.06	4.34	3.89	3.39	3.19
Annual average (kWh/m^2-day)	4.59	4.52	4.64	4.69	4.21
Annual (kWh/m^2-day)	1676	1649	1695	1712	1536

From the table above we find that there is a decrease of solar energy over the years. This has happened also at Calcutta, India, a neighboring station of Bangladesh.

Table 8: Variation of solar radiation over the years for Calcutta, India

Month	Measured data for Calcutta	
	1957-1978[1]	1992(Jan)-1996(Jun)[2]
Jan	4.22	3.77
Feb	5.03	4.18
Mar	5.79	5.39
Apr	6.32	5.81
May	6.53	5.87
Jun	4.96	4.71
Jul	4.64	4.22
Aug	4.47	4.34
Sep	4.48	4.32
Oct	4.53	4.26
Nov	4.38	3.66
Dec	4.1	3.55
Annual average (kWh/m^2-day)	4.95	4.51
Annual (kWh/m^2-day)	1810	1650

IMD: India Meteorological Department

1. A. Mani; Handbook of Solar Radiation, Allied Publishers, 1981
2. Courtesy, TERI, India

Climatological Solar Radiation model values of NREL as well as DLR values of GHI are in fine agreement with the measured experimental values of RERC for 1987-'89. But these NREL and DLR GHI values are higher than that for recent years. Monthly ratios of RERC/NREL and RERC/DLR have been used to tune the NREL and DLR data over the country.

The monthly tuning factors are given in the table below:

Table 9: Tuning factors for GHI values for NREL and DLR

Month	NREL	DLR
Jan	0.76	0.69
Feb	0.95	0.93
Mar	0.88	0.92
Apr	0.94	0.91
May	0.98	1.05
Jun	0.94	1.10
Jul	1.15	1.19
Aug	1.00	1.00
Sep	0.95	1.00
Oct	0.76	0.85
Nov	0.92	0.88
Dec	0.78	0.73

GHI maps have been obtained by using tuning factors and are shown in figures 4 and 5. For most of the country NREL and DLR values tuned to Dhaka data are very similar (about 2%variation). Estimated values from sunshine duration agree well with them. But for extreme eastern and northern regions NREL and DLR values differ a lot; 15-20% in the east and 9-10% in north. Measured values of sunshine duration data are not available for such locations for comparison. In order to reduce uncertainty RERC has developed a map of 10km×10km resolution by averaging the NREL and DLR values calculated for maps tuned to Dhaka. Figure 6 shows the map attained by averaging the two tuned maps.

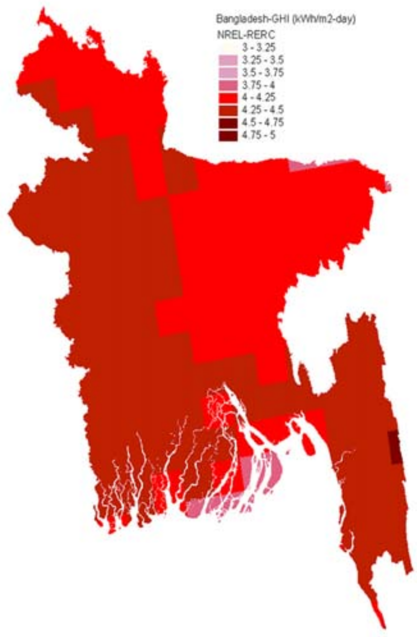


Fig 4: GHI map of NREL tuned to Dhaka data

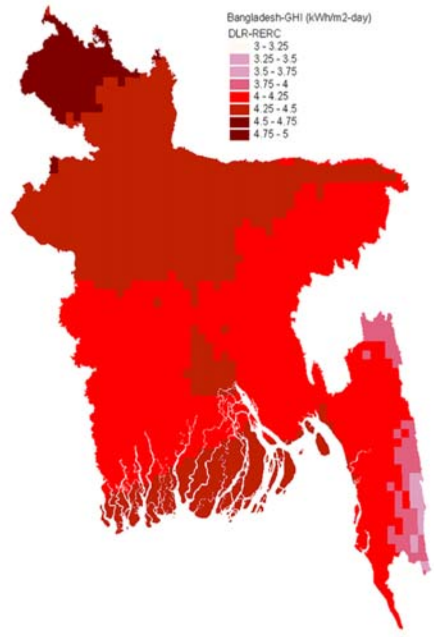


Fig 5: GHI map of DLR tuned to Dhaka data

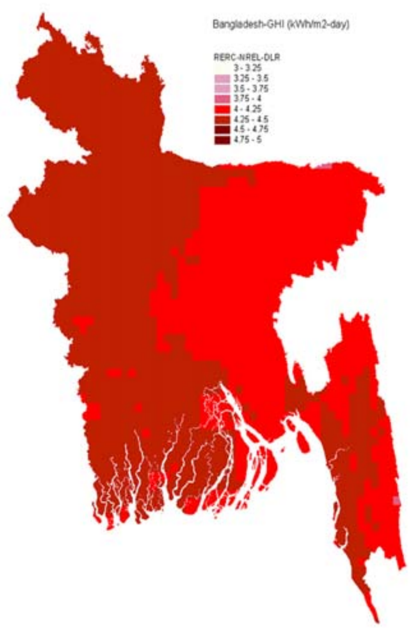


Fig 6: GHI map of RERC-NREL-DLR showing averaged NREL and DLR tuned values

Four monthly RERC-NREL-DLR GHI maps are given in the following figures.

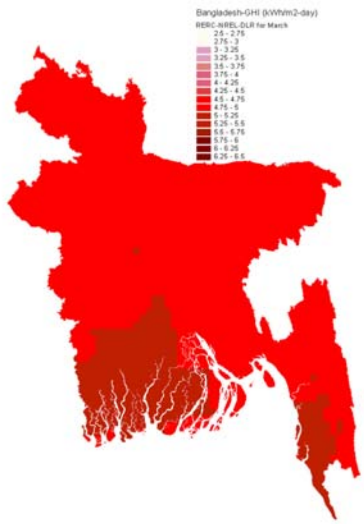


Fig 7: GHI map of RERC-NREL-DLR for March

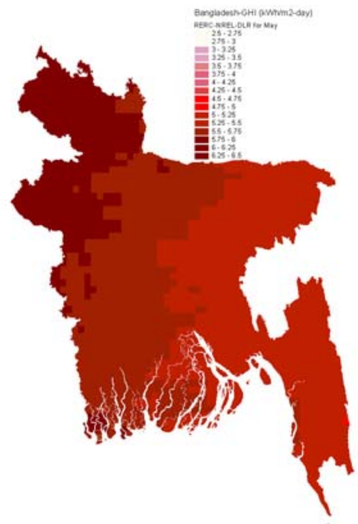


Fig 8: GHI map of RERC-NREL-DLR for May

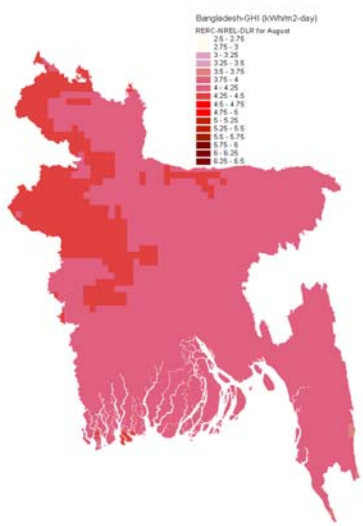


Fig 9: GHI map of RERC-NREL-DLR for August

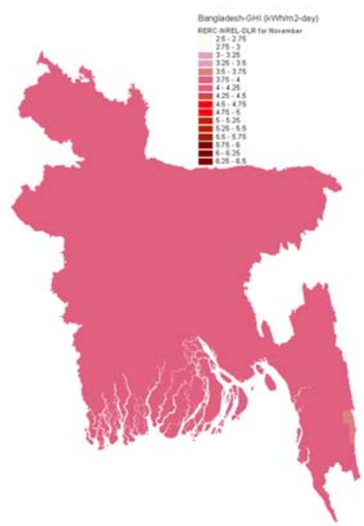


Fig 10: GHI map of RERC-NREL-DLR for November

7. **Estimation of DIF**

The monthly averaged daily diffuse radiation has been calculated using the Angstrom like correlation

$$\frac{\overline{H}_d}{\overline{H}} = c + d\frac{\overline{H}}{\overline{H}_0}$$

$\overline{H}$ is the monthly averaged daily global radiation on a horizontal surface, c and d are correlation coefficients. For best results months have to be grouped seasonally. The graphs are shown in the following figure.

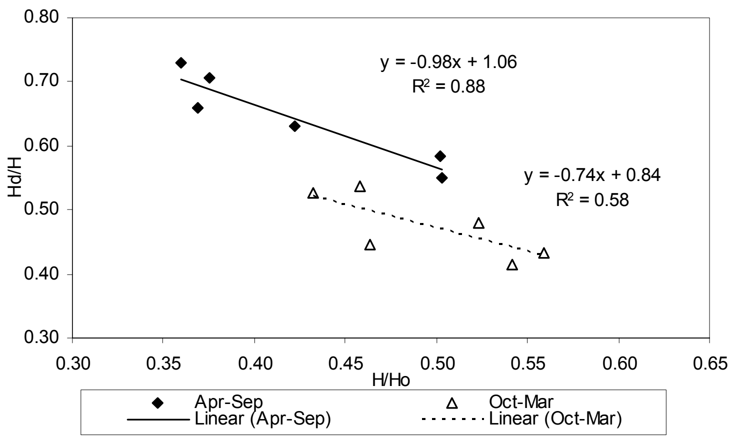


Figure 11: Correlation between monthly $\overline{H}_d / \overline{H}$ and $\overline{H} / \overline{H}_o$

For the correlation data period is Jan’03-Apr’05. The annual rms error is 0.11 kWh/m^2-day and percentage error is 4.6%.

Annual averaged daily measured data for Dhaka and estimated DIF values for BMD stations are shown on a map of Bangladesh in the following figure 12.

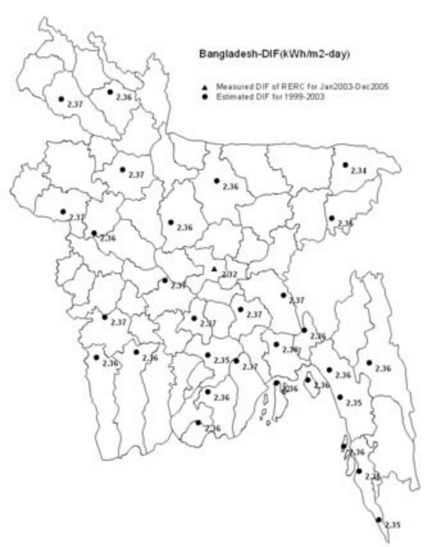


Figure 12: Annual Measured and Estimated DIF for RERC and BMD stations

8. Model computation of DIF values and map

NREL computed the diffuse irradiance for 40km×40km cells with CSR model and developed annual and monthly maps over Bangladesh for 1985-'91. The monthly tuning factors for NREL data are given below in Table 10.

Table 10: Monthly DIF (kWh/m^2-day) for Dhaka and tuning factors for NREL

	SWERA/RERC	NREL	Tuning factors
Month	**2003-05**	**1985-91**	**NREL**
January	1.72	1.52	1.14
February	1.99	2.15	0.93
March	2.34	2.52	0.93
April	2.90	3.07	0.94
May	3.11	3.12	1.00
June	2.84	3.40	0.83
July	2.74	3.13	0.88
August	2.77	3.01	0.92
September	2.52	2.76	0.92
October	1.90	1.77	1.07
November	1.60	1.59	1.00
December	1.38	1.25	1.11

Annual DIF map of NREL tuned to Dhaka together with 4 monthly maps are given below in figures 13 to 17.

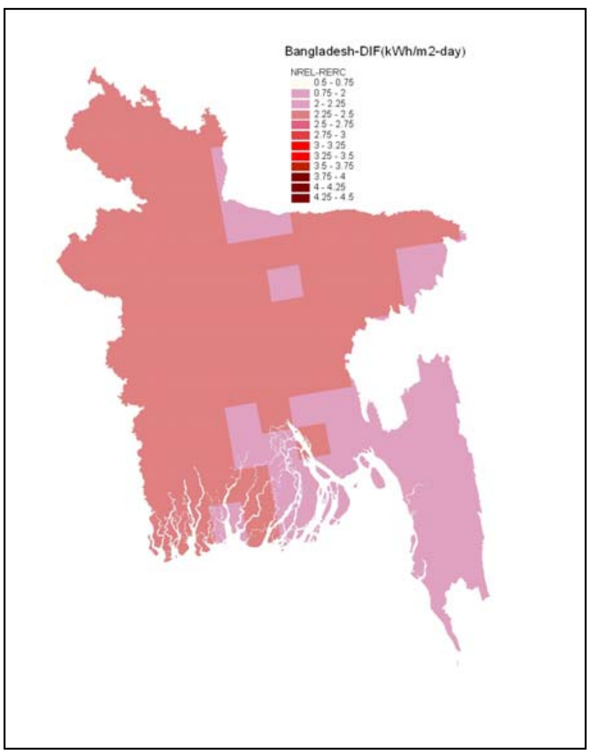


Figure 13: Annual DIF map of NREL tuned to Dhaka

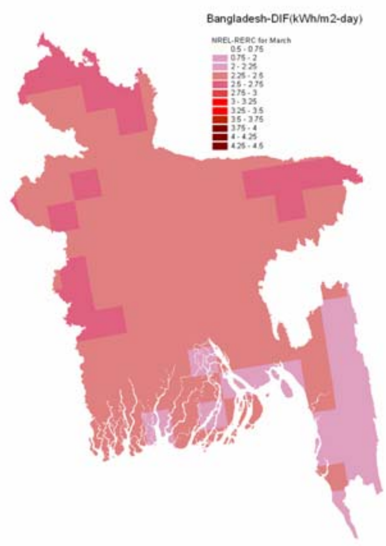


Fig 14: DIF map of NREL-RERC for March

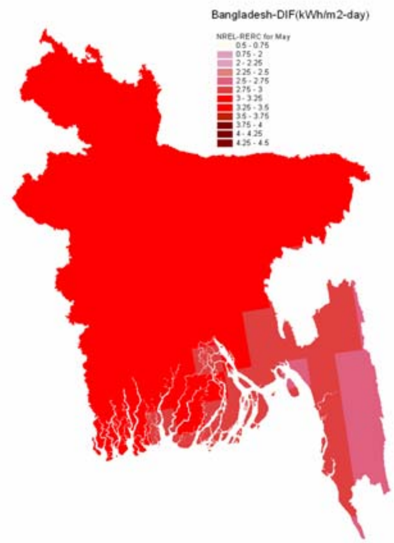


Fig 15: DIF map of NREL-RERC for May

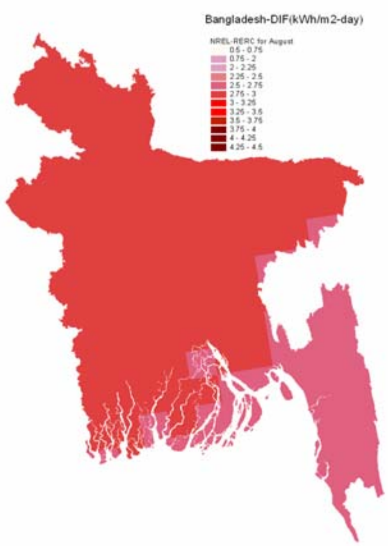


Fig 16: DIF map of NREL-RERC for August

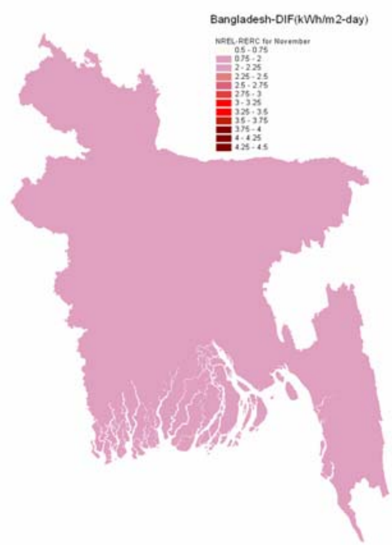


Fig 17: DIF map of NREL-RERC for November

9. Measurement and Estimation of Direct Normal Irradiance (DNI)

Direct normal irradiance (DNI) values can be obtained from DHI (=GHI-DIF) and the solar zenith angle. As solar zenith angle varies over hour and hourly GHI and DIF values are available at Dhaka only, experimental values of DNI is found for Dhaka. For other meteorologicla staions monthly ratios of measured DHI and DNI values for Dhaka have been considered the monthly zenith angle. The measured DNI values for Dhaka and estimated DNI values for BMD stations are shown in the following figure 18.

Figure 18: Annual Measured and Estimated DNI for RERC and BMD stations

10. Model computations of DNI and maps

1. NREL model

The model is based on the method described by Bird for the calculation of direct radiation perpendicular to the surface with a few modifications such as the use of a correction factor for the distance between Sun and Earth, and the use of Leckner's formula for transmittances of water vapor, ozone and other atmospheric gases (Iqbal, 1983). The aerosol transmittance is parameterized using the Angstron's method.

$$I_{d\lambda} = H_{0\lambda}\, D \tau_{\gamma\lambda}\, \tau_{a\lambda}\, \tau_{wv\lambda}\, \tau_{o\lambda}\, \tau_{g\lambda} \cos(\theta_0)$$

The $H_{0\lambda}$ is the extraterrestrial irradiance at the mean distance between Sun and Earth for the wavelength λ. D is the correction factor for the distance Sun - Earth, θ_0 is the solar zenithal angle and $\tau_{i\lambda}$ represent the transmittance functions for the radiative processes: Rayleigh scattering, scattering and absorption by aerosols; absorption by water vapor; absorption by ozone and absorption, respectively, by O_2 and CO_2 gases (SWERA web site).

2. DLR model

The calculation of *DNI* bases on the clear-sky model of Bird and Hulstrom (1981) as described in Iqbal (1983) which was modified by Schillings et al. (2004) for taking into account cloudy conditions with

$$DNI = 0.9751 \cdot I_o \cdot \tau_R \cdot \tau_{Gas} \cdot \tau_{Ozon} \cdot \tau_{WV} \cdot \tau_{Ae} \cdot \tau_{vis} \cdot \tau_{ir}$$

Each atmospheric transmittance coefficient τ_i is calculated separately using atmospheric input data (SWERA web site).

The clear-sky radiation is calculated each 20 minutes (10,30,50 minutes of each hour) for the maps and each 5 minutes (5,10,15,…,55,60 minutes each hour) for the time series. The influence of the clouds is taken into account hourly, therefore all maps (monthly and annual average daily sums) and time series are based on an hourly calculation of the radiation. The DLR -model output for *DNI* is for 10km×10km spatial resolution where for NREL it is 40km×40km resolution.

The monthly tuning factors for NREL and DLR are shown in the following Table 11.

Table 11: Monthly measured and model DNI values (kWh/m^2-day) for Dhaka

	SWERA/RERC	NREL	DLR	Tuning factors	Tuning factors
	03-05	1985-91	00 02 03	NREL	DLR
Jan	2.58	4.78	6.42	0.54	0.40
Feb	4.02	3.94	5.48	1.02	0.73
Mar	3.62	4.23	5.35	0.86	0.68
Apr	3.13	3.35	5.77	0.93	0.54
May	3.09	3.15	4.30	0.98	0.72
Jun	1.81	1.35	2.31	1.34	0.78
Jul	2.15	0.99	1.89	2.18	1.13
Aug	1.88	1.45	2.34	1.29	0.80
Sep	1.85	1.67	2.57	1.11	0.72
Oct	2.59	4.64	3.94	0.56	0.66
Nov	4.13	4.61	6.24	0.89	0.66
Dec	3.24	5.33	5.88	0.61	0.55

The DNI maps of NREL and DLR tuned to Dhaka data are shown in the following figures 19 and 20. Figure 21 represents the RERC produced DNI map by averaging the NREL and DLR data. Figures 22 to 25 are four monthly RERC-NREL-DLR DNI maps.

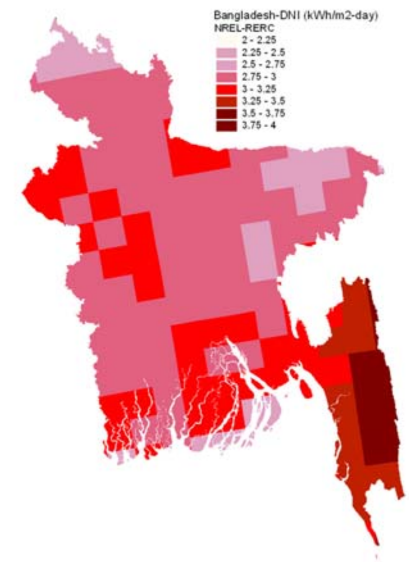


Fig 19: DNI map of NREL tuned to Dhaka data

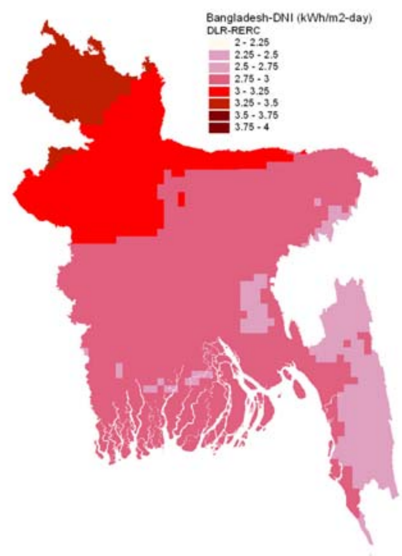


Fig 20: DNI map of DLR tuned to Dhaka data

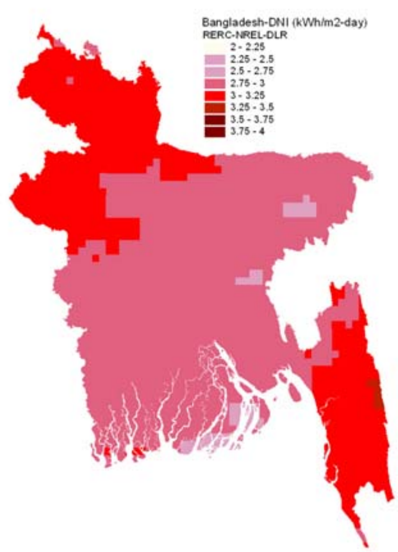


Fig 21: DNI map of RERC-NREL-DLR, showing averaged NREL and DLR tuned maps data

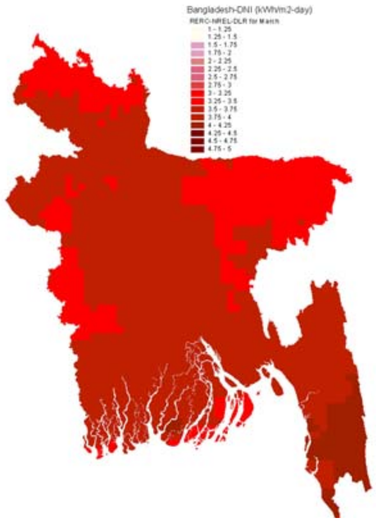


Fig 22: DNI map of RERC-NREL-DLR for March

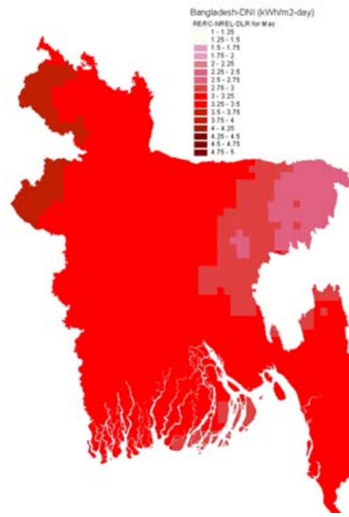


Fig 23: DNI map of RERC-NREL-DLR for May

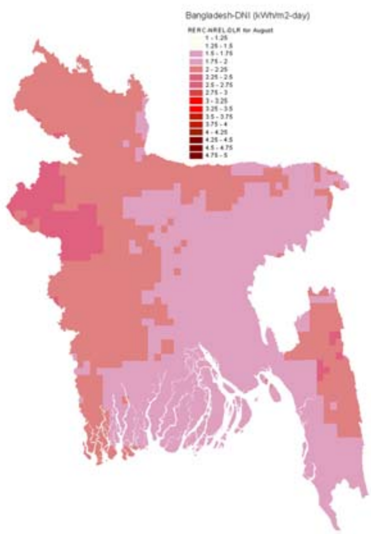


Fig 24: DNI map of RERC-NREL-DLR for August

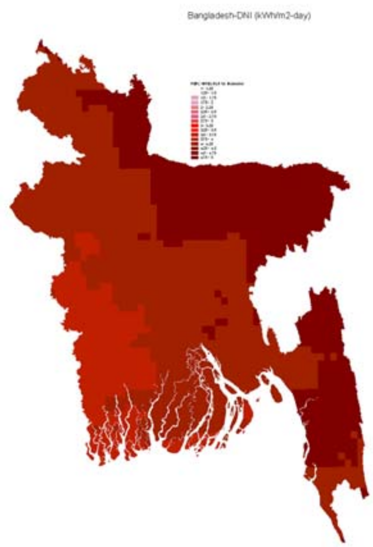


Fig 25: DNI map of RERC-NREL-DLR for November

11. Estimation of Tilted surface radiation

Flat-plate solar collectors absorb both beam and diffuse radiation components of solar radiation. To use horizontal total radiation data to estimate radiation on the tilted surface plane of a collector of fixed orientation, it is necessary to know R, the ratio of total radiaion on a tilted surface to that on the horizontal surface. The amount of solar radiation falling on a tilted surface is the sum of the beam and diffuse radiations falling directly on the surface and the radiation reflected on the surface from the surroundings. If one knows the tilt factor for a specific tilt angle for a location then he can easily estimate what will be the radiation on the tilted surface for Solar Home System.

The ratio of the beam radiation falling on a tilted surface to that falling on a horizontal surface is called the tilt factor (R_b) for beam radiation. For the case of a tilted surface facing south in the northern hemisphere, R_b and is given by

$$R_b = \frac{\cos\theta}{\cos\theta_Z} = \frac{\sin\delta\sin(\phi-\beta)+\cos\delta\cos\omega\cos(\phi-\beta)}{\sin\phi\sin\delta+\cos\phi\cos\delta\cos\omega}$$

where, θ is the angle between the beam radiation on a surface and normal to that surface, θ_z is the zenith angle, ϕ is the latitude, β is the tilt angle, δ is the declination for the average day of each month, ω is the hour angle for the tilted surface for the average day of the month.

The tilt factor R_d for diffuse radiation is the ratio of the diffuse radiation falling on the tilted surface to that falling on a horizontal surface. The value of the tilt factor depends upon the distribution of diffuse radiation over the sky and on the portion of the sky dome seen by the tilted surface. Assuming that the sky is an isotropic source of diffuse radiation, we have

$$R_d = (1+\cos\beta)/2$$

Assuming that the reflection of the beam and diffuse radiations falling on the ground is diffuse and isotropic and that the reflectivity is ρ, the tilt factor for reflected radiation is given by

$$R_r = \rho(1-\cos\beta)/2$$

where ρ is the surface albedo. The monthly surface albedo values are employed from NASA and these lie between 0.12 and 0.16.

Thus the hourly tilt factor, R can be given by

$$R = \frac{H_T}{H} = (1-\frac{H_d}{H})R_b + \frac{H_d}{H}R_d + R_r$$

Table 12: Hourly Tilt factors for Latitude tilted south facing surface at Dhaka

Hour angle	± 7.5	± 22.5	± 37.5	± 52.5	± 67.5	± 82.5	± 97.5
Jan	1.14	1.15	1.16	1.17	1.20	1.37	
Feb	1.12	1.12	1.12	1.13	1.14	1.21	
Mar	1.05	1.05	1.05	1.04	1.02	1.00	
Apr	0.99	0.99	0.98	0.97	0.95	0.93	0.95
May	0.96	0.96	0.95	0.93	0.91	0.89	0.97
Jun	0.95	0.95	0.94	0.92	0.90	0.88	0.78
Jul	0.95	0.95	0.94	0.92	0.89	0.86	0.76
Aug	0.97	0.97	0.96	0.95	0.93	0.89	0.82
Sep	1.00	1.00	1.00	0.99	0.98	0.96	0.70
Oct	1.06	1.07	1.08	1.08	1.08	1.13	
Nov	1.17	1.17	1.19	1.22	1.27	1.62	
Dec	1.19	1.21	1.23	1.26	1.36	1.53	

Tilt angles should be chosen so that the solar devices can get significant available solar radiation. In summer the sun's path is short and it shines almost on the zenith at noon. But in winter the sun path is long and it has a path closer to horizontal at noon. Hence if we keep the solar device horizontal in summer it will get more sunlight at noon and if we keep the device tilted in winter from the horizon it will get more sunlight. One can also track the sun both in the sun's direction of path and the time of the day. In Bangladesh a study shows that if one simply change the tilt angle at 40^0 for winter (October-February) and 10^0 for summer (March-September) then he can achieve higher tilt factors.

Table 13: Hourly Tilt factors for 10 and 40 degree combination south facing tilted surface at Dhaka

Hour angle	± 7.5	± 22.5	± 37.5	± 52.5	± 67.5	± 82.5	± 97.5
Jan	1.16	1.17	1.19	1.21	1.26	1.54	
Feb	1.12	1.12	1.13	1.14	1.17	1.29	
Mar	1.04	1.04	1.03	1.03	1.02	1.01	
Apr	1.01	1.01	1.01	1.00	0.99	0.98	0.99
May	1.00	1.00	0.99	0.98	0.97	0.96	1.00
Jun	0.99	0.99	0.99	0.98	0.97	0.96	0.92
Jul	0.99	0.99	0.99	0.98	0.97	0.95	0.91
Aug	1.00	1.00	1.00	0.99	0.98	0.97	0.93
Sep	1.01	1.01	1.01	1.01	1.00	0.99	0.88
Oct	1.04	1.04	1.06	1.07	1.07	1.16	
Nov	1.19	1.20	1.24	1.28	1.38	1.93	
Dec	1.24	1.26	1.29	1.36	1.52	1.79	

To estimate monthly average tilt factor Liu and Jordan proposed the following equation

$$\overline{R} = \frac{\overline{H}_T}{\overline{H}} = \left(1 - \frac{\overline{H}_d}{\overline{H}}\right)\overline{R}_b + \frac{\overline{H}_d}{\overline{H}}\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right)$$

Here for a south facing surface

$$\overline{R}_b = \frac{\overline{H}_{bT}}{\overline{H}_b} = \frac{\cos(\phi-\beta)\cos\delta\sin\omega'_s + (\pi/180)\omega'_s\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + (\pi/180)\omega_s\sin\phi\sin\delta}$$

where, ω_s is the sunset hour angle and ω'_s is the sunset hour angle for the tilted surface for the average day of the month, which is given by

$$\omega'_s = \min\begin{bmatrix}\cos^{-1}(-\tan\phi\tan\delta), \\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\end{bmatrix}$$

where "min" means the smaller of the two items in the bracket.

Monthly tilt factors are given in figure 26

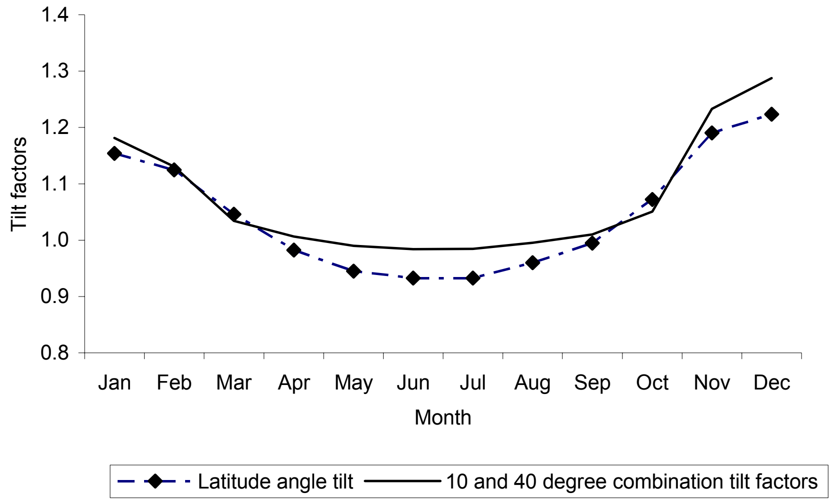


Figure 26: Monthly tilt factors for Dhaka

To find the tilted surface radiation one has to multiply GHI data by tilt factor. From the above figure 26 it is clear that the total radiation will decrease if one keeps the surface at latitude tilt angle in summer season at Dhaka. To get higher values from the solar system one may practice to tilt the surface, two times over the year as above tilt angles.

For BMD stations for which monthly GHI and DIF values have been estimated from sunshine duration, monthly tilt factors for latitude tilted surface have been computed and are shown in the following figure 27.

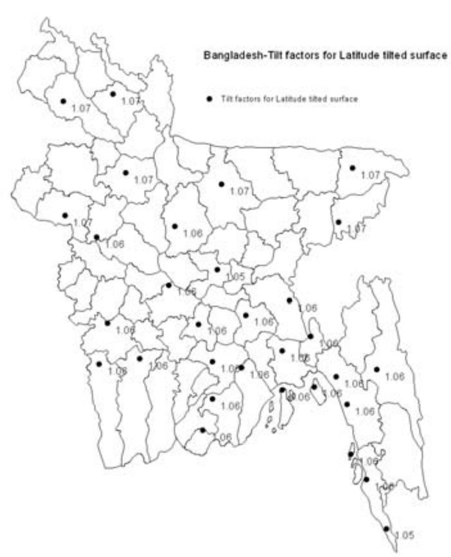


Figure 27: Annual Tilt factors for Latitude tilted surface for all BMD stations

12. **Model computation of tilt factors**

For estimating irradiances on latitude tilted surfaces over Bangladesh, NREL used the algorithm developed by Hay and Daves. The latitude tilted surface radiation map by NREL is shown in the following figure 28.

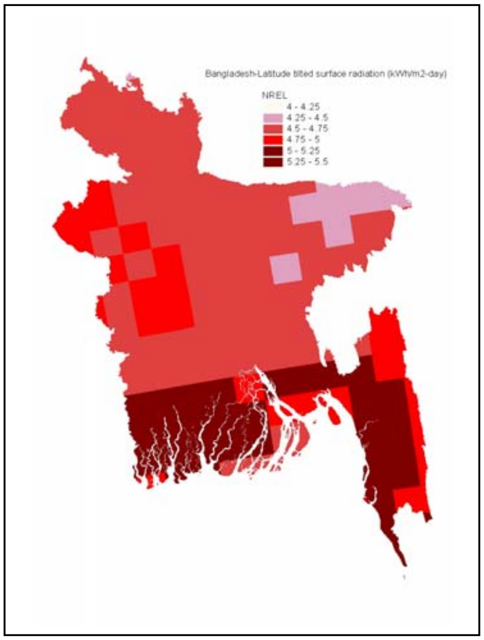


Figure 28: Annual latitude surface radiation by NREL

13. Typical Meteorological Year (TMY) by NREL

A representative database of weather data for the 1-year duration is known as Typical Meteorological Year (TMY). A TMY is a data set of hourly values of solar radiation and meteorological elements. It consists of months selected from individual years concatenated to form a complete year. TMY is defined as a year which sums up all the climatic information characterizing a period as long as the mean life of the system.

NREL generated the TMY dataset from hourly GHI, DIF, DNI, relative humidity, wind speed and ambient temperature. They developed the TMY values for 8 stations over Bangladesh. The stations are given in the Table 13.

Table 13: Stations for which TMY has been developed

Station	Lat	Long	Elev
RANGPUR	25.73	89.23	34
BOGRA	24.85	89.37	20
SYLHETI	24.90	91.88	35
ISHURDI	24.13	89.05	14
DHAKA	23.77	90.38	9
JESSORE	23.18	89.17	7
CHITTAGONG	22.27	91.82	6

COX'S_BAZAR	21.43	91.97	4

The values of TMY GHI for Dhaka are given in Table 14.

Table 14: TMY values of GHI

	Year	NREL
Jan	1980	4.19
Feb	1989	4.95
Mar	2002	5.48
Apr	1987	5.83
May	1985	5.54
Jun	1989	4.95
Jul	1999	4.48
Aug	1997	4.73
Sep	2000	4.72
Oct	1988	4.66
Nov	1997	4.18
Dec	1996	3.98
Annual average (kWh/m^2-day)		**4.81**

Section 3

ASSESSMENT OF BANGLADESH WIND RESOURCE

Introduction

For wind energy utilization in Bangladesh, sufficient information on wind speed and power density is not available. Some measurements have been done and some are going on at around 10–30m above the surface of the earth but reliable data are not available at 50m height which is a preferred hub height for many wind generators. Under the "Solar and Wind Energy Resource Assessment (SWERA) – Bangladesh" project, a part of the global project of SWERA funded by UNEP / GEF, the KAMM (Karlsruhe Atmospheric Meso-scale Model) and WAsP (Wind Atlas Analysis and Application Program) have been used to assess the wind resource of Bangladesh by developing wind maps for speed and power density at the height of 50m above the ground level with a resolution of 5km x 5km. For this purpose at Renewable Energy Research Centre (RERC), Dhaka University, wind data have been collected from different sources. Information on surface roughness, obstacles close to monitoring stations and terrain for the locations have been obtained by visiting the measurement sites and WAsP, a micro-scale modeling tool, has been used to predict and develop wind atlas for selected locations. RISOE, Denmark has done KAMM analysis and a cross validation between the WAsP analysis at RERC and KAMM studies has been made to generate final wind resource maps over Bangladesh.

Wind Speed Measurement in Bangladesh

A previous study showed that for 31 wind monitoring stations of Bangladesh Meteorological Department (BMD), situated in built up areas, wind speed is low near the ground level at the height of around 10 meter. In 1996-97 under the WEST project Bangladesh Centre for Advanced Studies (BCAS) with the support of Local Government Engineering Department (LGED) measured wind speed and direction at 25m height for seven locations near the seacoast. GTZ, a German Organization, also measured wind speeds for another three coastal location at a height of 20m. Bangladesh Council for Scientific and Industrial Research (BCSIR) measured wind speed for Dhaka (inland), Teknaf (coast side) and Saint Martin (island) locations from 1999–2001. Presently LGED is measuring the speed and direction at 20 locations all over Bangladesh under the WERM project at heights of 20 and 30m. In 2004, BPDB came forward to install a grid connected wind generation system after getting some data from their wind mast at 50m height at Feni. The data are yet to be validated.

Wind Speed Data

For the wind energy assessment study in the coastal areas, data have been collected from different organizations and table 1 shows the status of the collected data and figure1 shows the locations of wind monitoring stations. Again table 2 shows the geographical positions and heights of the anemometers at the wind monitoring locations in the coastal areas with their averaged wind speed values and measuring period.

Table 1: Status of the collected data

Organizations	Interval	Measuring Instrument	Anemometer Height	Collected by RERC
BMD	3 hourly	Cup anemometer with mechanical / electrical recorder	Around 10m	*3 hour intervals (1981 – 2001) for most of the stations*
BCAS (WEST Project)	10 minute	Cup anemometer with data logger (Campbell)	25m	*The raw data has been collected*
GTZ (TERNA Project)	10 minute	Cup anemometer with data logger (WICOM EL)	20m	*Monthly average wind speed data.*
BCSIR	1 hour	Cup anemometer with data logger	20 and 30m	*Monthly average daily wind speed*

Table2: Measured wind speed at different heights and places in the coastal areas

Organizations	Location	Position		Anemometer Height (m)	Ave Speed (m/s)	Measuring period
		Lat	Long			
BMD	Mongla	22.33	89.60	10	1.5	1991-2000
	Khepupara	21.99	90.22	15	1.9	
	Patuakhali	22.35	90.34	12	1.1	
	Bhola	22.69	90.64	10	0.6	
	Hatiya	22.43	91.10	10	**	
	Sitakunda	23.58	91.70	10	**	
	Sandwip	22.48	91.43	10	1.6	
	Chittagong	22.27	91.82	5	2.4	
	Kutubdia	21.81	91.85	14	1.7	
	Cox's Bazar	21.44	91.97	13	1.9	
	Teknaf	20.86	92.29	7	0.8	
BCAS	Kuakata	21.82	90.12	25	4.5	09/96-08/97
	Charfassion	22.19	90.83	25	4.0	
	Noakhali	**	**	25	2.9	
	Chittagong	22.20	91.78	25	3.8	
	Kutubdia	21.86	91.84	25	4.4	
	Cox's Bazar	21.70	91.96	25	3.2	
	Teknaf	20.85	92.27	25	2.8	
BCSIR	Teknaf	20.85	92.28	10	3.5	01/01-04/02
	Sant Martin	20.63	92.32	30	4.7	
GTZ	Feni	**	**	20	4.0	06/96-05/97
	Anwara	**	**	20	4.4	
	Teknaf	**	**	20	4.3	

** missing data

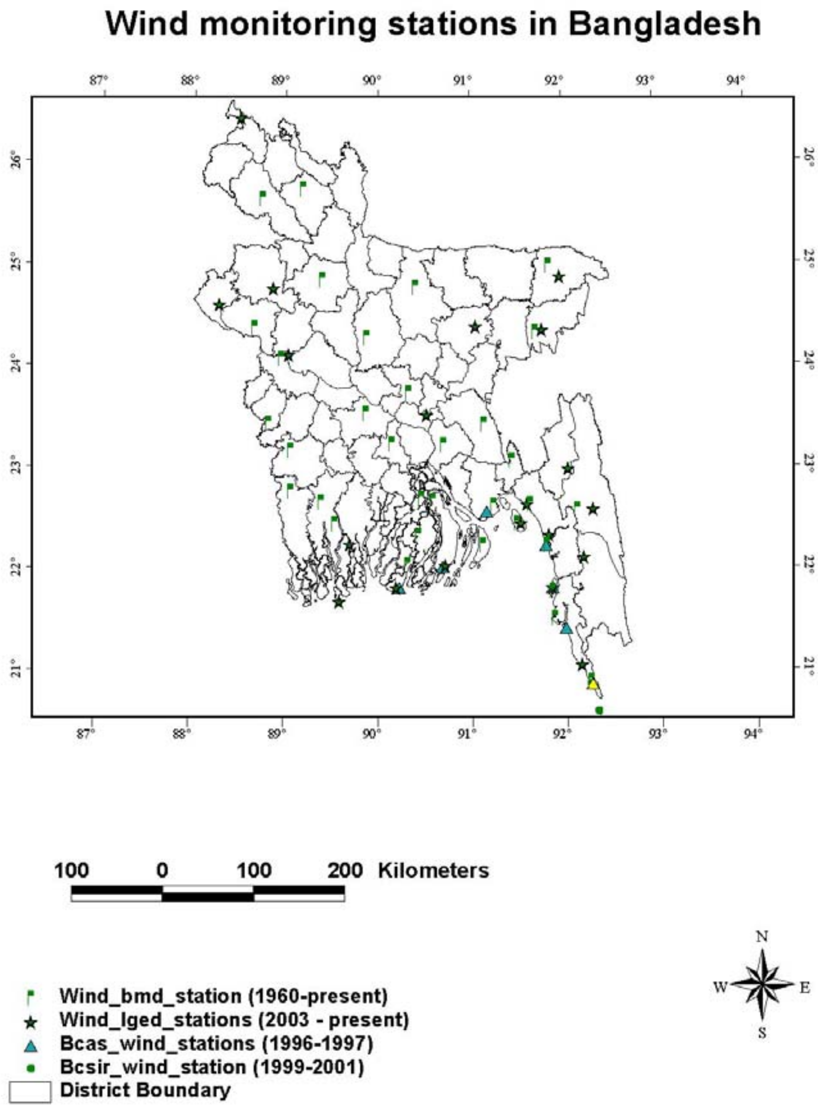


Figure 1: Wind monitoring stations in Bangladesh

Data Analysis

Twenty years (1981 – 2000) of BMD data and one year (Sept96 – Aug97) of BCAS raw data has been used for the analysis. BMD has 3 hour interval data where for BCAS it is 10 minute. BMD data was measured by manual recording whereas BCAS measured using electronic data logger for digital recording. For other organizations, time series data are not available for WAsP analysis.

As BMD has the measured data for a long period a detailed analysis has been done using the BMD data and figure2 shows the variation of wind speed for BMD locations during the period of 1981–2000. It has been found that BMD data gives low values due to the obstacle effect by trees and buildings close to the met stations. Daily and monthly analyses have been done for the BCAS locations and figure3 shows that the seasonal effect is quite strong in Bangladesh. During monsoon period (May – Aug), wind speed is high and for the rest of the year it is low. Figure4 shows the diurnal variation for two of the coastal locations. Maximum wind speed appears in the afternoon and minimum in the early morning over the day. Figure5 shows the speed for BCAS locations and nearby BMD stations.

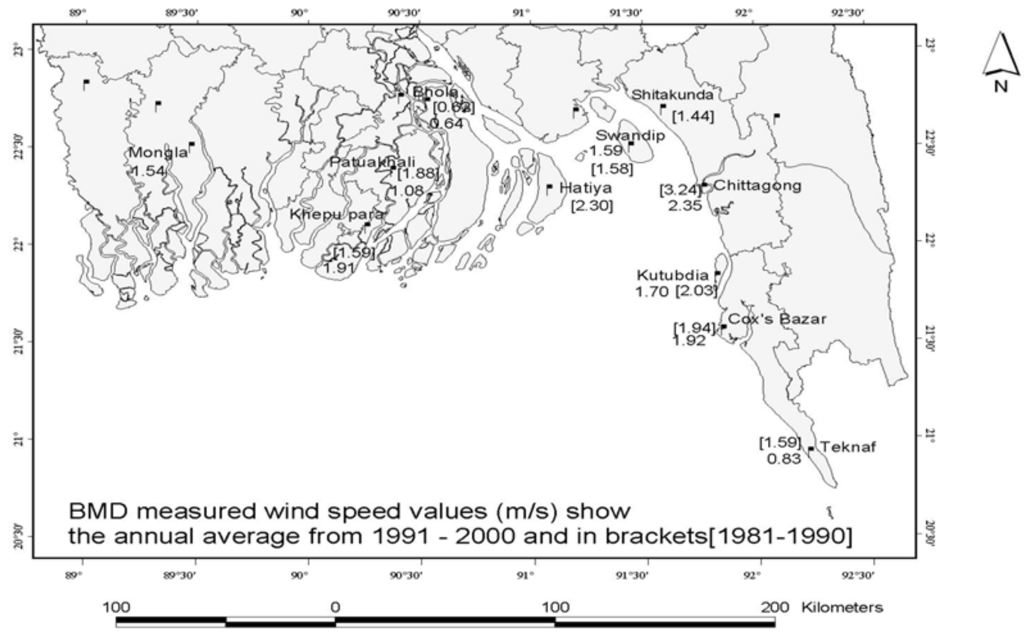


Figure 2: BMD measured wind speed for the period of 1981 – 2000

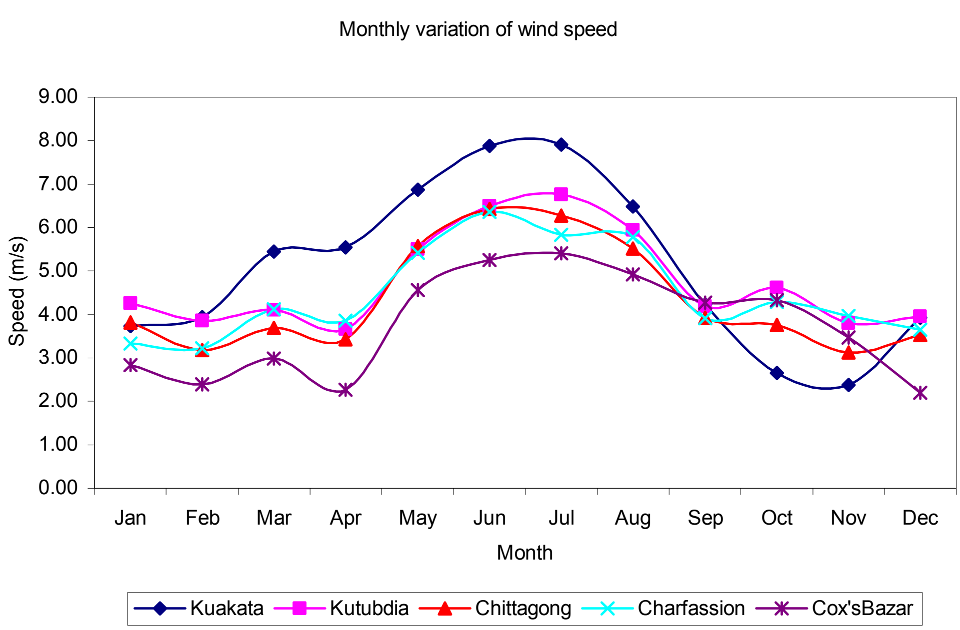


Figure 3: Monthly variation of wind speed for five BCAS locations at 25m height

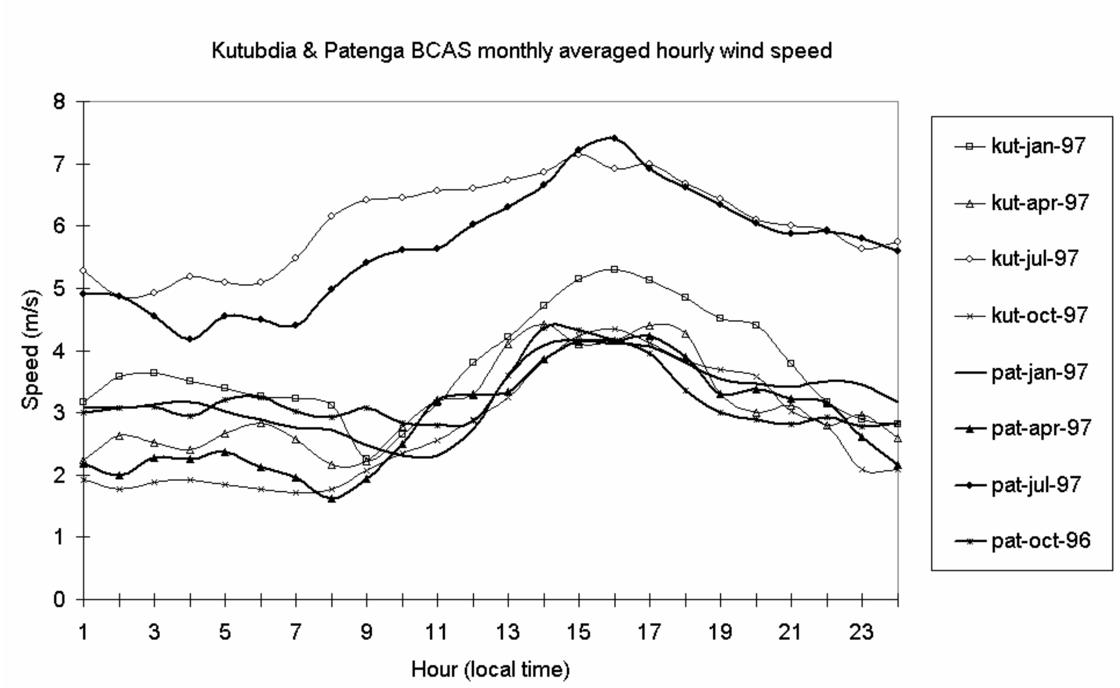


Figure 4: Diurnal wind speed variation of two coastal locations for different months at 25m height

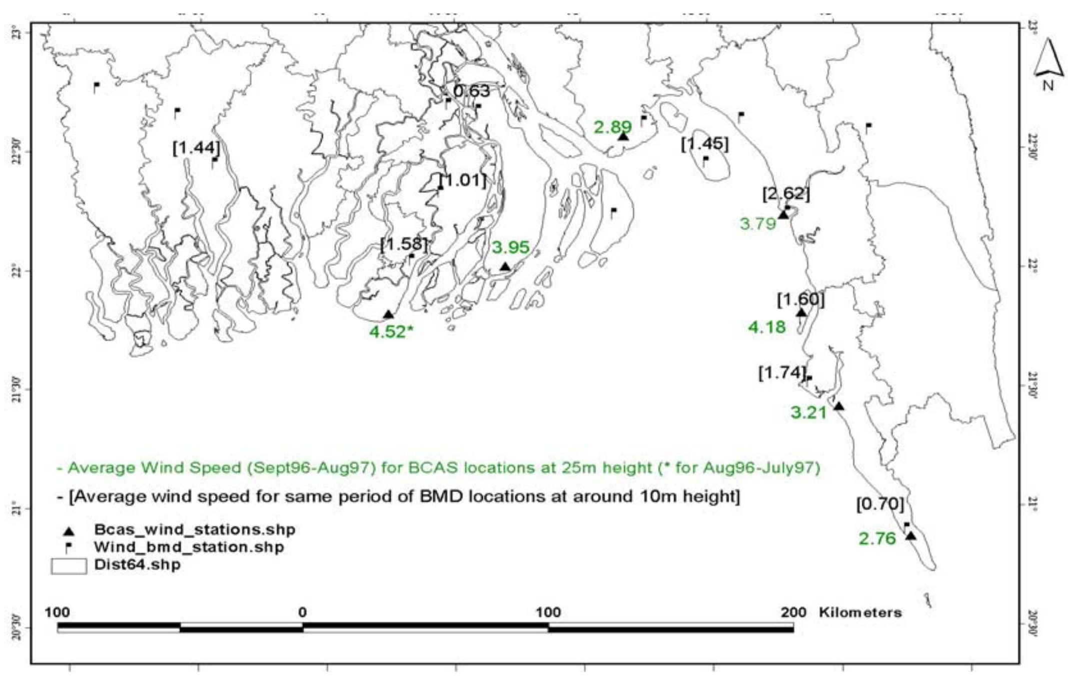


Figure 5: Average wind speed for BCAS (25m height) and BMD (10m height) locations

Wind Energy Assessment - Techniques

Logarithmic and Power Law

Ground-level obstacles such as vegetation, buildings, and topographic features tend to slow the wind near the earth surface. Since the effect of these obstacles decreases with height above ground, wind speeds tend to increase with height above ground. This variation of wind speed with height which is called *wind shear* could be described with two mathematical models: power law and logarithmic law.

The wind speed profile or the change in wind speed with height is found to be given by the power law

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} \quad - \quad - \quad - \quad - \quad - \quad - \qquad (1)$$

Here α is power law index, V_1 and V_2 are speeds at height Z_1 (anemometer) and Z_2 (hub) respectively. This law fits data quite accurately for limited ranges of heights for example between 10 and 100m but not between 1 and 100m. The value of power law index, p of power law is equal to 1/7 and this 1/7 power law may be considered as a special case of the exponential relations for high surface wind speed. Wind speed researchers, however, have found that in practice the power law exponent depends on temperature, season, terrain roughness, and several other factors.

Again the air flow between the lower atmosphere and tall vegetation changes the elevated position of the active surface as shown in Figure 6 and therefore the logarithmic wind profile, $V = \frac{U}{k} \ln \frac{Z}{Z_0}$, given in should be modified as;

$$V = \frac{U}{k} \ln \frac{Z - d}{Z_0} \quad --- \quad - \quad - \quad - \quad - \quad - \; (2)$$

where U is termed the friction velocity which is equal to $\frac{\sqrt{\tau}}{\rho}$, τ is the surface sharing stress representing the force exerted on the surface by the air and ρ is the density of air, Z is the height and Z_0 is the aerodynamic surface roughness height, d is called zero plane displacement ($d = \frac{2h}{3}$) and h is the height of the vegetation stand. The value of Z_0 for different types of surfaces varies widely between fractions of a cm to a meter. Ratio of equation 2 for two heights may be then used to estimate the wind speed for predicted height.

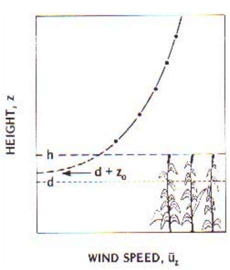
From the raw data analysis it has been found that the hourly and monthly wind speed variation in coastal part of Bangladesh is very high and therefore power density seems to be prospective but power law will not be good enough to use for wind speed prediction. Site visits were done for most of the BMD and BCAS stations near the coast to collect the details on surface roughness, land use information, terrain information and condition of surround obstacles. Surface roughness values were taken from the land use information and log law used to predict the wind speed at 25m height for the BCAS location using the data from nearby BMD stations which have been shown in the table3;

Table 3: Measured and predicted wind speed (m/s) at 25m height for BCAS locations using BMD data and log law for the period of Sept96 to Aug97

	Kuakata			Charfassion			Patenga			Kutubdia			Teknaf		
Month	BMD	M	P	BMD	M	P	BMD	M	P	BMD	M	P	BMD	M	P
Sept	1.3	3.6	3.0	0.7	3.3	1.9	2.1	3.4	3.3	1.1	3.6	2.7	0.6	3.5	1.4
Oct	1.0	*2.2*	2.4	0.9	3.7	2.3	2.6	3.2	4.2	1.2	4.0	2.8	0.5	3.3	1.3
Nov	0.5	1.9	1.1	0.4	**	**	0.6	2.6	1.0	0.8	3.2	1.9	0.4	2.3	0.9
Dec	0.7	3.4	1.6	0.5	3.1	1.2	1.0	3.0	1.5	1.1	3.4	2.7	0.4	1.4	1.0
Jan	0.8	3.2	1.8	0.6	2.8	1.6	1.0	3.3	1.5	1.2	3.7	2.9	0.7	2.1	1.7
Feb	0.8	3.4	1.9	0.7	2.7	1.8	1.3	2.7	2.1	1.3	3.3	3.1	0.7	1.9	1.7
Mar	1.5	4.8	3.6	1.1	3.5	3.0	2.6	3.1	4.2	1.5	3.5	3.6	0.8	2.3	2.0
Apr	1.4	4.9	3.4	1.0	3.3	2.7	2.0	2.9	3.2	1.3	3.1	3.0	0.7	1.7	1.7
May	2.6	6.3	6.1	1.8	4.8	4.7	4.0	5.0	6.3	2.0	4.9	4.7	1.4	3.1	3.6
Jun	2.9	7.3	6.8	1.6	5.8	4.4	4.4	5.8	7.0	2.7	5.9	6.3	0.7	3.3	1.7
Jul	2.4	*7.3*	5.7	1.2	5.2	3.3	5.2	5.7	8.2	2.7	6.2	6.3	0.8	4.3	2.0
Aug	3.1	**	**	1.6	5.2	4.4	4.5	4.9	7.2	2.1	5.3	5.0	0.8	4.0	1.9
Ave	**1.6**	**4.4**	**3.4**	**1.0**	**3.9**	**2.9**	**2.6**	**3.8**	**4.1**	**1.6**	**4.4**	**3.8**	**0.7**	**2.8**	**1.7**

Where M and P represent the measured and predicted values and ** for missing of raw data

Comparison between measured and predicted values (table3) shows a remarkable difference. It may be assumed that the quality of BMD data is not good enough as it records manually at 3 hour intervals and the locations are surrounded by lots of obstacles. In case of BCAS, stations are close to the coastal sea-shore area with fewer obstacles. The effect of obstacles is shown in Figure7. The anemometer mast for BMD stations is also placed on the top of the roof of the met stations (a typical BMD met station and a BCAS station are showing in figure8). The useable height of the anemometer for met stations buildings are another problem to predict wind speed using log law. Also terrain and direction wise roughness effects are other problems for calculation. All of these effects are not considered in the log law analysis. So, prediction may not be accurate enough.



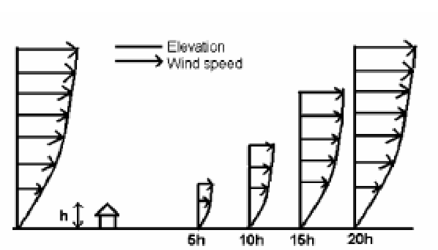


Figure 6: Position of the active surface due to tall vegetation   Figure 7: Effect of obstacles

(a) (b)

Figure 8: a) BMD met station building showing the position of anemometer on the roof and b) a BCAS monitoring station

Energy Assessment using WAsP (Wind Atlas Analysis and Application Program)

WAsP is a state of the art modeling tool which requires time series data. It is based on the physical principles of flow in the atmospheric boundary layer and takes into account the effects of different surface roughness conditions, sheltering effects due to buildings and other obstacles, and the modification of the wind imposed by the specific terrain height variations around the met station. Latitude, longitude and anemometer height are the pre-requirements to input the data for any location. Considering the effects for obstacles, roughness and terrain the WAsP develops a wind atlas for a region around (10x10) km^2 in area. Figure9 shows the WAsP methodology to generate regional wind climatology or wind atlas and to predict wind climate over the region.

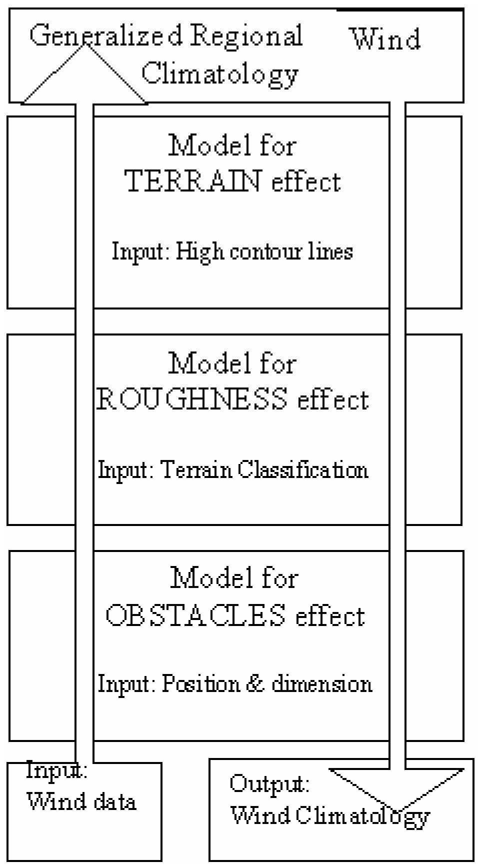


Figure 9: WAsP methodology

Models for obstacles, roughness and terrain effect

In the WAsP, base map of any location is used to draw the roughness and contour lines according to the land use information and terrain description of the location. Based on the surface characteristics and corresponding roughness values, roughness models both for BMD and BCAS locations have been developed by WAsP. These roughness models show that the roughness value for coastal areas lies in between 0.001 and 0.03 m and as the met station is situated within a built up area, the roughness value lies in between 0.1 and 0.4m.

It may be mentioned that WAsP develops the roughness model considering the land use information around 5 to 10 km area for all directions from the point of interest.

For BMD stations as the mast is on the roof of the building (mentioned above), according to Lars Landberg's study "The mast on the House", hill effect has been introduced in the WAsP model by modifying the ground into 1:5 slope and it is done by drawing two separate closed contour lines one for the building height and another one for the ground height above the sea level. In this case the anemometer height to be used should be its height from the roof.

Again, the BMD station is situated in an inhabited locality and the sheltering effect, due to obstructions for wind flow by buildings and trees close to the met station, is to be considered for that location. The height and depth of an obstacle, its angular position and distance from the monitoring mast and the porosity (0–1) have to be taken into consideration to develop the obstacle model. In this model, the obstacles that are found within the slope (1:5) range with heights equal to or less then the height of the met station need not be considered. For BCAS location, obstacles are very less than that of BMD and there are only some rows of trees with low density. Figures 10, 11 and 12 show the roughness and obstacle models that are developed in the WAsP program and terrain information that are used.

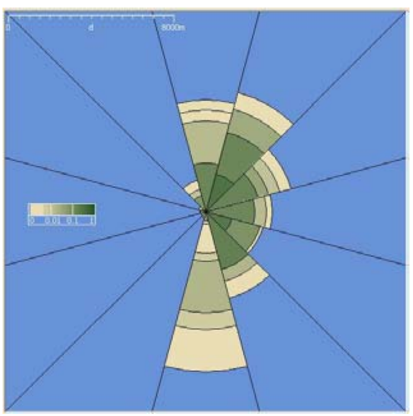


Figure 10: Roughness model for Kuakata BCAS

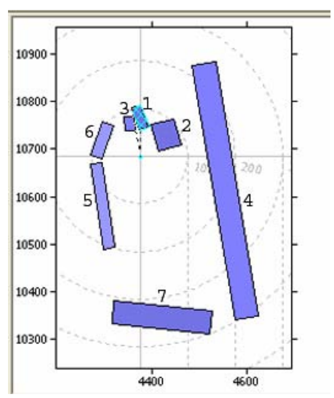


Figure11:Obstacles model for Kuakata BCAS

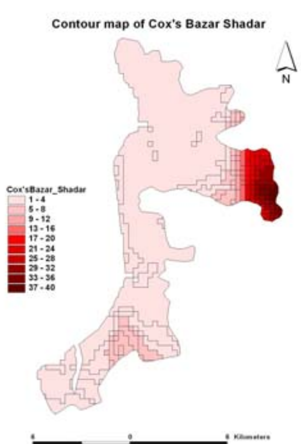


Figure 12: Terrain or contour map of Cox's Bazar location that are used in WAsP

Using the logarithmic wind profile, surface-layer similarity laws, geostrophic drag law and the geostrophic wind, the stability model, the roughness change model, shelter model, the orographic model from the terrain information and analyzing the time series raw data of wind speed and direction WAsP shows the average wind speed, power density, frequency response, wind rose and then a wind atlas/regional wind climate in the form of Weibull parameters.

Developed Wind Atlas

After analyzing the artificial hill effect due to the met building, effect of obstacles close to the anemometer mast, roughness of the locality and terrain information the monthly and annual wind atlas for the coastal locations have been developed using 1 year (Sept96–Aug97) as well as 10 years (1991–2000) three hourly time series data of BMD and 1 year (Sept96–Aug97) 10 minute interval time series data of BCAS. A comparative study was done between the measured and predicted values for BMD and BCAS locations from the developed wind atlas using 1 year data for both of the locations (table5). It was found that the obstacles, terrain and roughness effects are high for BMD stations and data are manually recorded for 3 hourly intervals and therefore wind atlas obtained by BMD data was not accurate enough compared to that of BCAS. BCAS wind atlas gives lower prediction of power density than that of BMD. Therefore, for conservative prediction wind atlas developed using 1 year data of BCAS has been used for further assessment. The prediction should become more accurate if data were available for a longer period.

Table 5: Measured and Predicted values of wind speed (U) and power density (P) for BMD and BCAS locations for the period of Sept96-Aug97 for Kutubdia.

	BMD (13m)		BCAS (25m)	
Month	Measured (U / P)	Predicted (using atlas developed by BCAS data) (U / P)	Measured (U / P)	Predicted (using atlas developed by BMD data) (U / P)
Jan	1.4 / 03	1.6 / 04	3.8 / 059	3.5 / 055
Feb	1.5 / 04	1.5 / 04	3.5 / 044	3.5 / 053
Mar	1.7 / 12	1.8 / 09	3.9 / 086	4.0 / 102
Apr	1.5 / 06	1.6 / 08	3.6 / 074	3.1 / 057
May	2.6 / 68	2.3 / 23	5.0 / 183	4.8 / 332
Jun	2.6 / 51	2.7 / 22	6.1 / 207	5.2 / 393
Jul	2.6 / 33	2.9 / 23	6.3 / 224	5.2 / 251
Aug	2.3 / 21	2.5 / 20	5.5 / 182	4.4 / 148
Sep	1.4 / 03	1.6 / 06	3.6 / 053	3.0 / 037
Oct	1.5 / 09	1.8 / 11	4.0 / 097	2.8 / 059
Nov	1.1 / 02	1.5 / 03	3.5 / 036	2.7 / 035
Dec	1.4 / 03	1.5 / 04	3.7 / 049	3.6 / 071
Annual	**1.9 / 24**	**2.0 / 14**	**4.4 / 125**	**4.3 / 190**

Table6 shows the wind speed and power density at 25, 30, 50 and 70m heights for four roughness conditions which have been taken from the developed wind atlas for the locations. It shows that wind speed at 50m height for all the locations varies from 4.0m/s to 5.8m/s for the coastal sea-shore areas (roughness in between 0.00–0.03m). Power density at the same height also shows that some of the locations are quite potential for wind generators. Figure13 shows the frequency distribution and Weibull parameters for the locations at 50m height with a roughness value of 0.03m. It is also found that the Weibull shape factor for the coastal areas varies from 1.59 to 1.89.

Table6: Predicted Wind speed (Sp in m/s) and Power density (PD in w/m^2) in three prospective coastal locations for different heights and roughness conditions obtained from the developed wind Atlas for the locations.

Locations	Height		Roughness			
	(m)		**0.00 m**	**0.03 m**	**0.10 m**	**0.40 m**
			Sp / PD	**Sp / PD**	**Sp / PD**	**Sp / PD**
Kuakata	25		4.9 / 174	3.7 / 090	3.3 / 066	2.8 / 039
	30		5.0 / 181	3.8 / 097	3.5 / 072	2.9 / 044
	50		5.3 / 209	4.3 / 119	3.9 / 092	3.4 / 061
	70		5.4 / 237	4.6 / 136	4.3 / 107	3.7 / 074
Charfassion	25		4.7 / 149	3.5 / 076	3.2 / 055	2.7 / 033
	30		4.8 / 155	3.7 / 082	3.3 / 061	2.8 / 037
	50		5.0 / 179	4.1 / 101	3.7 / 078	3.2 / 052
	70		5.2 / 203	4.4 / 117	4.1 / 092	3.5 / 063
Kutubdia	25		5.4 / 208	4.1 / 105	3.6 / 076	3.1 / 045
	30		5.5 / 218	4.2 / 113	3.8 / 084	3.2 / 051
	50		5.8 / 251	4.7 / 141	4.3 / 108	3.7 / 071
	70		6.0 / 286	5.1 / 165	4.6 / 128	4.0 / 088

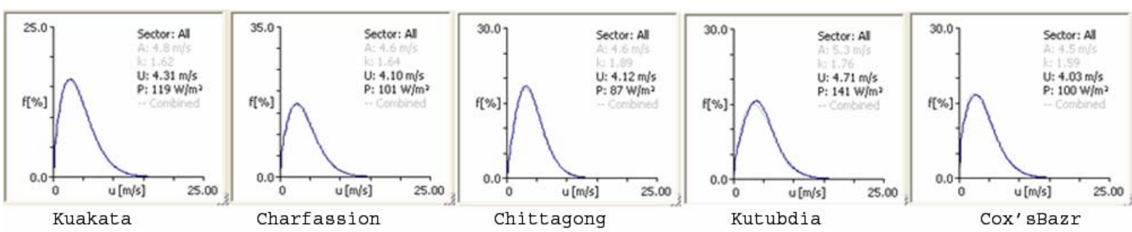


Figure 13: Frequency distribution and weibull parameters at 50m height and for 0.03m roughness value for five coastal locations

		R-class 0 (0.000 m)	R-class 1 (0.030 m)	R-class 2 (0.100 m)	R-class 3 (0.400 m)
Height 1 (z = 10 m)	m/s W/m²	4.93 165	3.40 68	2.95 44	2.32 21
Height 2 (z = 25 m)	m/s W/m²	5.39 208	4.07 105	3.64 76	3.05 45
Height 3 (z = 50 m)	m/s W/m²	5.79 251	4.71 141	4.27 108	3.68 71
Height 4 (z = 100 m)	m/s W/m²	6.28 331	5.60 221	5.09 166	4.45 109
Height 5 (z = 200 m)	m/s W/m²	6.94 475	6.96 446	6.28 325	5.43 206

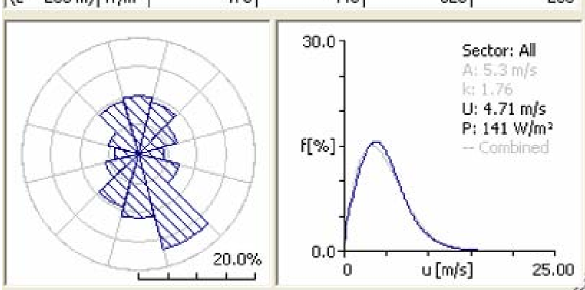


Figure 14: Wind Atlas for Kutubdia

Using the developed wind atlas annual wind speed and power density have been predicted at 50m height for the BCAS locations considering the roughness, obstacles and terrain effects. WAsP predicts wind resource considering direction wise effects due to obstacles, roughness, terrain and the measured wind speed. It also uses the global position of met station to consider the effect of geostropic wind.

Wind Resource Map – selection of good location

The developed wind atlas for the coastal locations using BCAS data for 1 year, shown in tables6 can be used to generate the wind resource map at different heights with the help of (100 x 100) m^2 grid cells. WAsP calculates and shows the Weibull parameters, wind speed and power density for each of the grid cells taking into account the roughness, obstacles and terrain effects for the desired location. To develop a more accurate wind resource map using WAsP, a micro-scale modeling tool, long period time series data along with detailed land use information map (base map) are very essential. The wind resource map for Kutubdia at 50m height is shown in Figure 15 along with the minimum, maximum and average values of Weibull parameters, wind speed and power density for all over the island. Monthly wind speed and power density for three good locations (TS-1, TS-2, TS-3), considering only the terrain and roughness effects, have been obtained. As the selected sites are close to the sea-shore, it may be expected that trees and buildings may not be high enough for the obstacle effect. It was found that these sites (speed is around 5.5 m/s) are better than the BCAS location of Kutubdia.

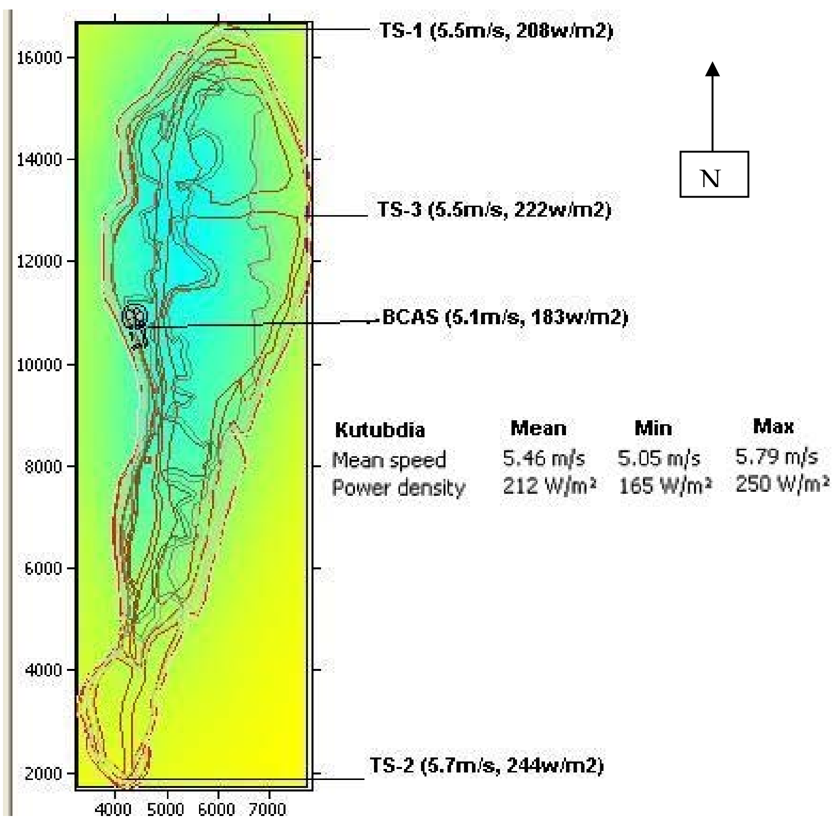


Figure15: Wind resource for Kutubdia at 50m height

Based on the wind data measurement study at different coastal locations (figure1, tables 2 and 6) by BMD, BCAS, GTZ, BCSIR and the micro-scale analysis by WAsP it is found that wind speed at 30m height is above 4 m/s for most of the coastal areas. And due to large hourly and monthly variation power density is also higher than most locations having the same average wind speed. Therefore, most of the coastal areas are good for small wind turbines with a hub height of 30m (table6). Prediction at or above 50m height (table6), using micro-scale modeling and considering the roughness, obstacles and terrain effect, shows that some areas in Kutubdia, St Martin's, Sawndip, Hatya, Charfassion Islands, and some of the sea-site of inlands like Kuakata, Feni should be more attractive than the other areas where wind power density is above 200 W/m^2 and according to the wind resource classification system these areas should be marginal and fair for large turbines (figure15). It may be mentioned that for the first time a 1MW grid connected wind electricity generation system in Feni, a coastal inland, and a 10KW wind-solar hybrid system in St Martin's Island are now being run, depending on short time measurement at around 30 – 40m height, which may boost up the renewable based grid connected and hybrid system implementation in Bangladesh. But till now we don't have the performance data from these systems.

KAMM Analysis

The Karlsruhe Atmospheric Mesoscale Model (KAMM) is a 3D, non-hydrostatic, and incompressible mesoscale model. KAMM is able to run as a "stand-alone" model, i.e. the model can be run by using only the large-scale forcing in the form of a single vertical profile of geostrophic wind and virtual potential temperature. Hence, it is not necessary to nest the mesoscale model within a larger model that must supply the boundary conditions. It uses a technique called the statistical-dynamical downscaling. The long-term large-scale wind influencing the region of interest is determined using available (NCEP/NCAR) reanalysis data. This atmospheric meso-scale model which runs typically at 5 km resolution generates maps of wind resource and wind speed and direction distributions for any location within the modeling domain. Detailed of this model is described in Annexure- B along with the cross validation procedure and results of WAsP and KAMM Analysis. Figure17 shows how to calculate the local wind climate using WAsP and KAMM result.

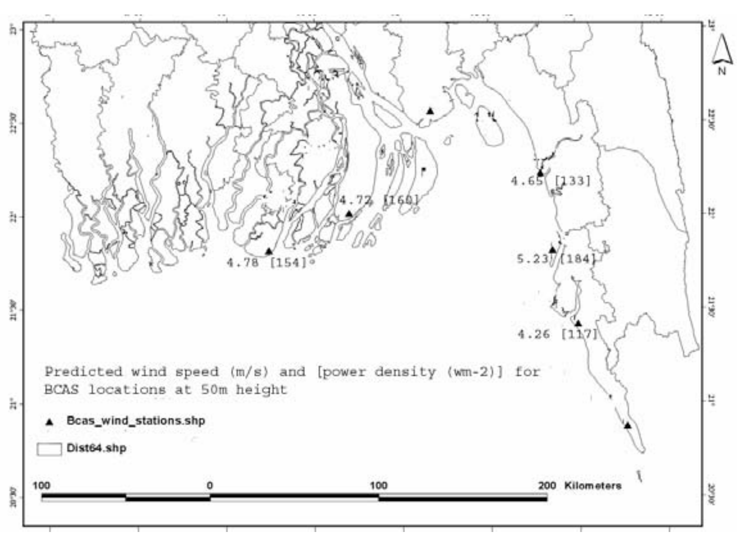


Figure16: Wind Speed and Power Density at 50m height for the BCAS locations

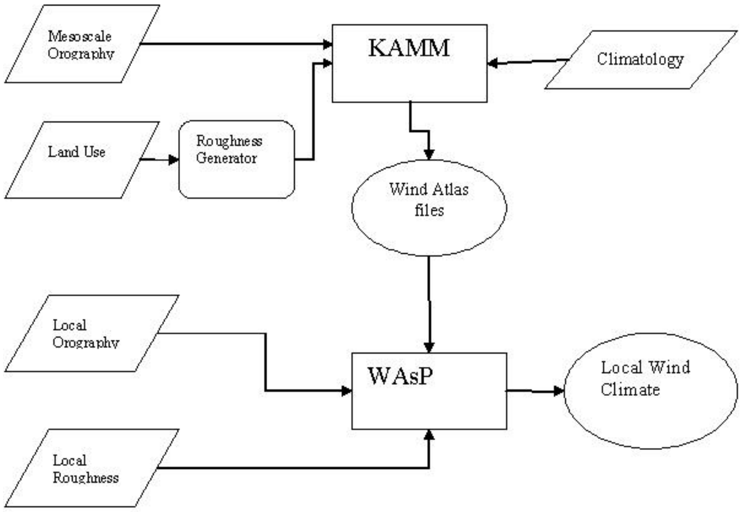


Figure17: The combination of KAMM and WAsP to calculate the local wind climate

Based on the WAsP analysis using the data for the BCAS coastal locations and the KAMM analysis final simulated maps have been generated for mean annual wind speed (figure18) and power density (figure19) at 50m height above the ground level for the overall Bangladesh at a resolution of 5km x 5km as well as wind speed and power density for the roughness condition of 0.03m (Appendix1)

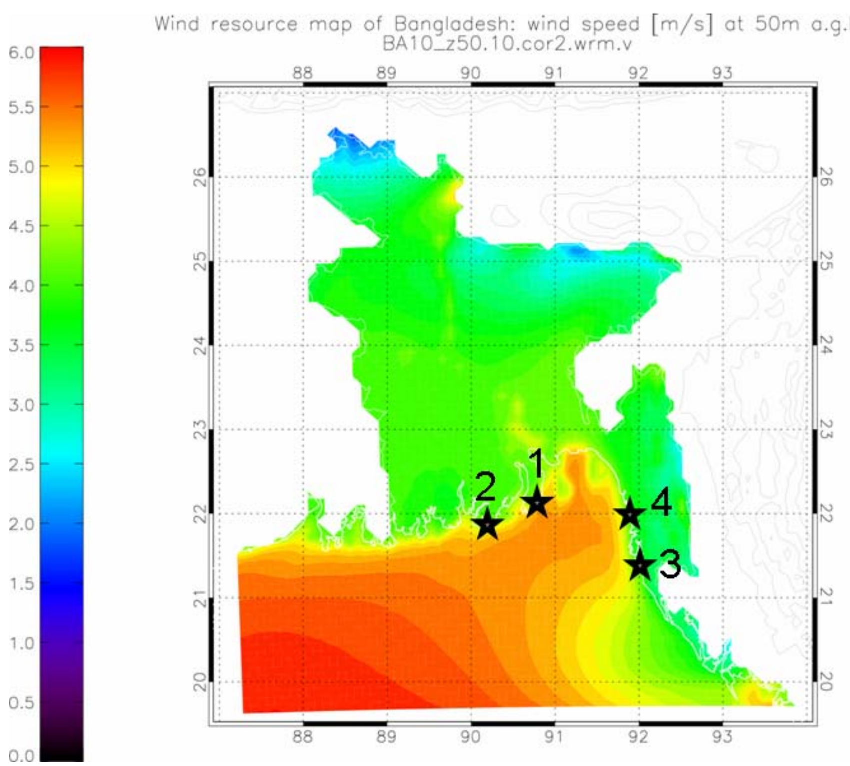


Figure 18: Annual mean simulated wind speed at 50 m a.g.l and also indicating 4 monitoring stations of BCAS

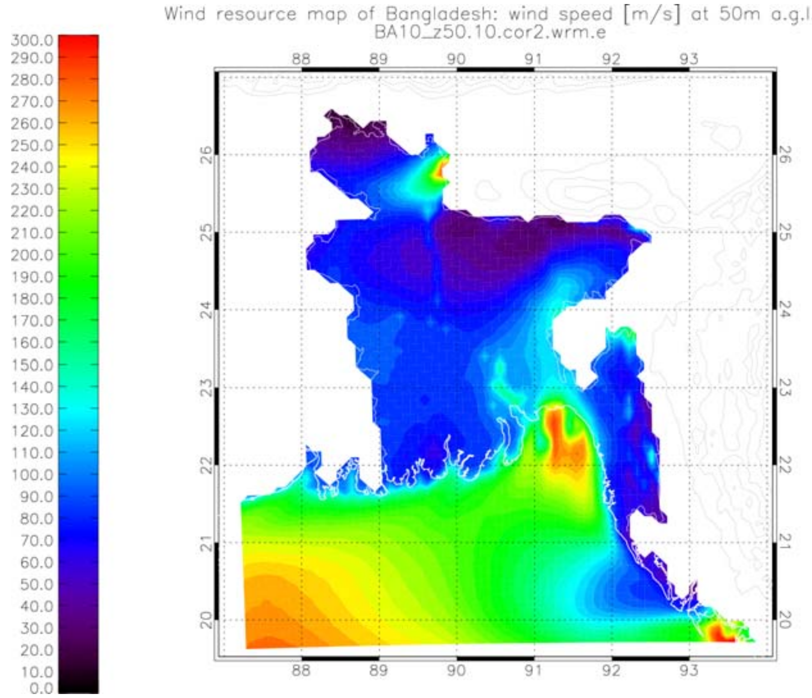


Figure 19: Annual mean simulated wind power density at 50 m a.g.l.

It is found that in the coastal belt areas an annual mean wind speed at 50m height is estimated to be in between 4.5 to 5.5 m/s. The map (figure18) shows that higher wind speed around 6m/s may be found south of Noakhali coast between Sawndip and Hatya. Again a small area near Brahmaputra river in the border of Kurigram shows a higher wind speed around 5m/s. It may be mentioned that measurement study by BPDB at 4 coastal locations shows around 7m/s wind speed at 50m height which does not agree with the WAsP analysis and the resource map developed by RISOE.

Recommendation:

1. Long term measurements of wind speed at 50m height should be made for locations where predicted speed is high according to the wind resource map and WAsP analysis in order to go for wind electricity generation.
2. For all prospective areas detailed maps as shown in figure15 should be produced which require measurements and detailed land use information.
3. For off grid coastal areas hybrid generation using wind and PV or diesel should be started.

Integration of solar and wind info into SWERA toolkit

A GIS based GeoSpatial Toolkit has been developed for Bangladesh using the global solar radiation on horizontal and tilted surface at latitude angle along with the value for direct normal incidence at a resolution of (10x10) and (40x40) sqr-km. Wind power density at the resolution of 5x5 sqr-km has also been incorporated along with other related information like locations of conventional power plant, road, river network, airport etc. This toolkit is free for all and can be found in the SWERA website; http://swera.unep.net

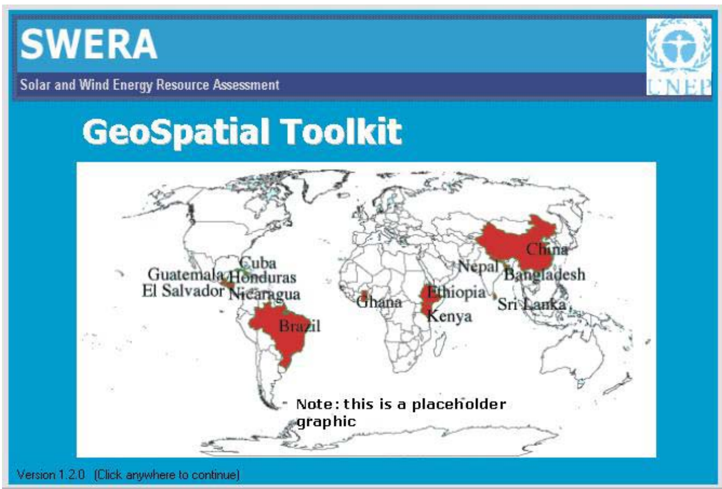


Figure20: Starting page of GeoSpatial Toolkit

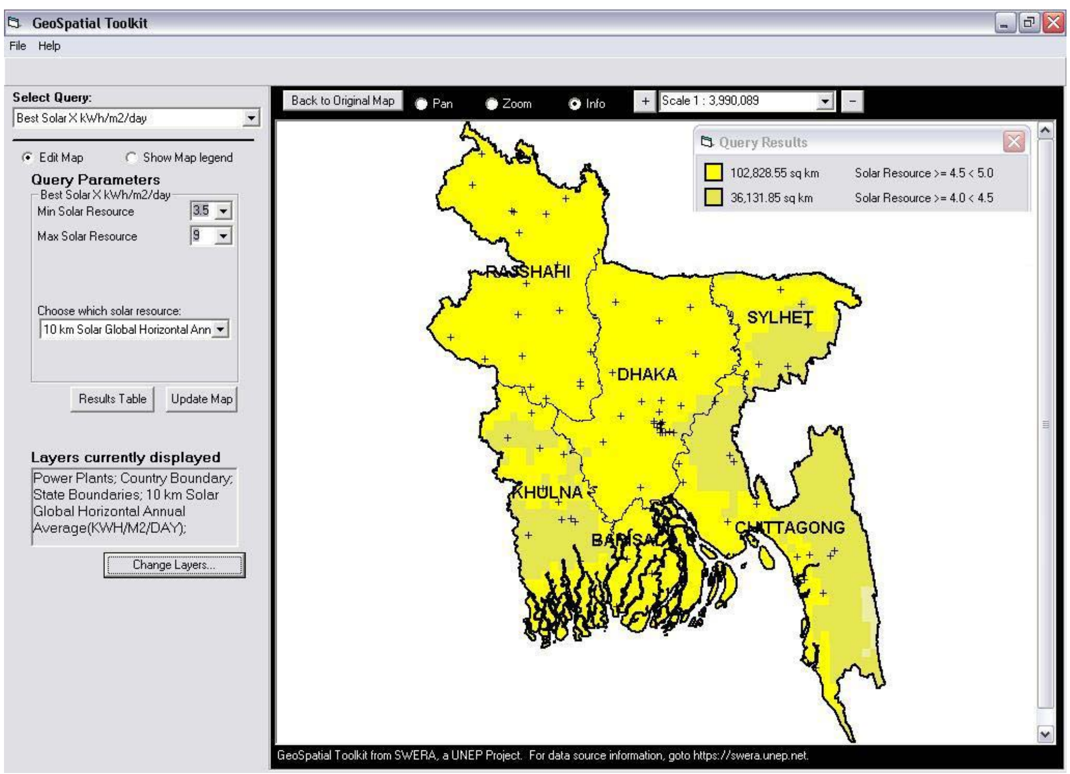


Figure21: View in GeoSpatial Toolkit

Section 4

Application of SWERA Products

The product, SWERA – Bangladesh GeoSpatial Toolkit, that has been developed can be used to design any kind of solar and wind energy system. Here in this part some of the analyses have been given as case studies;

Off-grid Electrification

From the overall assessment of solar and wind energy in Bangladesh it has been found that some of the coastal part in the southern region should be useful for wind energy utilization. In terms of solar energy, some important locations over the country have been considered. GHI data for all the locations have been taken and to minimize the seasonal effects (8 / 40) degree combination as tilt angle has been done.

Different types of combination for solar, wind and diesel gen-set system have been considered for the selected locations. Monthly load curves have been generated based on the normal load use information considering CFL – 4 pcs with 20W each, Fan – 2 pcs with 80W each, TV – 1 pc with 80W each and Mobile Charger - 1 pc with 5W each for household. For 400 household it gives 100 kW peak load with an energy demand of 400 kWh/day. Load demand due to seasonal variation has also been taken. Figure1 and 2 show the monthly variation of generated primary load curve and also the hourly variation for two seasonal months. Table1 shows the cost of different parameters that are chosen as input for all the calculations;

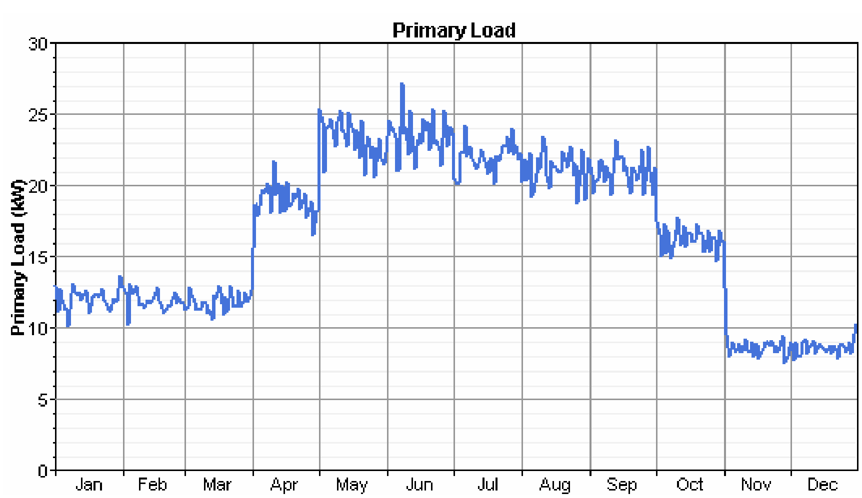


Figure1: Monthly averaged load demand curve for 400 household users

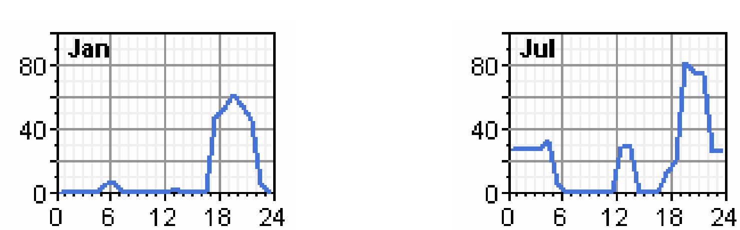


Figure2: Hourly load demand curve for the months of a) January and b) July

Table1: Cost of different component that has been considered for the analysis
(Exchange rate $1 USD = 65.00 BDT)

Parameter	Capital Cost (Taka)	Replacement Cost (Taka)	O & M (Taka)
PV module	300,000 BDT/kW	240,000 BDT/kW	500 BDT/year
Wind Turbine*	130,000 BDT/kW	100,000 BDT/kW	500 BDT/year
Battery	7,000 BDT/kWh	6,000 BDT/kWh	50 BDT/year
Generator	20,000 BDT/kW	18,000 BDT/kW	0.70 BDT/hour
Diesel	33 BDT/Litre		
Inverter	27,000 BDT/kW	22,000 BDT/kW	50 BDT/year
Other cost	20,000 BDT/kW		

*Considering wind turbine of Fuhrlander 100 model (100 kW Capacity)

Other constraints;
Annual real interest rate : 5%
Project life time : 25 years
Subsidy (optional) : 15,000 BDT / home
Maximum Capacity shortage : 5%

All the case studies for generating 100kW peak loaded renewable based electrification system have been analyzed both technically and economically using HOMER and RETScreen software for some of the important locations considering the same parameter cost and other constraints which are given below;

Case1: Kutubdia Island – 100 kW Renewable based off-grid electrification system

Previous studies and analysis indicates that most of the coastal island and some of the inland costal areas should be viable for wind electricity generation. As Kutubdia is one of the most promising islands in Bangladesh which has excellent wind resource data for best location in Kutubdia from WAsP analysis is used in this simulation. Tables 2 and 3 show results of the analysis. It is clear that wind-diesel system should be best for the islands. For the best locations and also for other prospective places zero emission system (PV-Wind or wind only) can be chosen if excess energy (figure3) is used to meet other seasonal energy demand. Both the subsidized and non-subsidized systems have been considered. For hybrid systems only one diesel genset has been taken where as for diesel only system one additional genset is needed for continuous running. It is clear from the analysis that hybrid system is more economical than the diesel only system. No doubt that there is an additional important environmental benefit for the hybrid systems.

Table2: Technical sizing and economic information for different renewable based system comparing diesel only system for Kutubdia Island where wind speed is 5.5m/s;

System (off-grid)	Component Size			Initial Capital (10^6 BDT)	NPC (10^6 BDT)	RE Fraction	Excess Energy (%)	Cost of Energy (BDT/kWh)	
	PV (kW)	Wind (kW)	DG (kW)					With subsidy	Without subsidy
Wind -Diesel	---	100	40	21.49	31.99	0.85	28	13.7	16.3
PV-Wind-Diesel	10	100	40	24.69	34.21	0.89	30	14.3	16.8
PV - Diesel	10	---	65	07.85	42.95	0.10	01	19.4	22.0
Diesel only	---	---	110	03.45	61.08	0.00	27	---	29.7
PV – Wind	50	100	---	36.12	38.78	1.00	40	17.2	19.8
Wind only	---	300	---	45.66	47.78	1.00	73	21.8	24.4

Table3: Same as table2 but for wind speed of 4.0m/s;

System (off-grid)	Component Size PV (kW)	Wind (kW)	DG (kW)	Initial Capital (10^6 BDT)	NPC (10^6 BDT)	RE Fraction	Excess Energy (%)	Cost of Energy (BDT/kWh) With subsidy	Without subsidy
Wind -Diesel	---	100	60	17.86	42.40	0.50	21	19.0	21.5
PV-Wind-Diesel	10	100	60	21.62	43.31	0.57	19	19.4	22.0
PV - Diesel	10	---	65	07.85	42.94	0.10	01	19.4	22.0
Diesel only	---	---	110	03.45	61.08	0.00	27	---	29.7
PV – Wind	70	200	---	55.10	58.43	1.00	43	27.2	29.8
Wind only	---	---	---	---	---	---	---	---	---

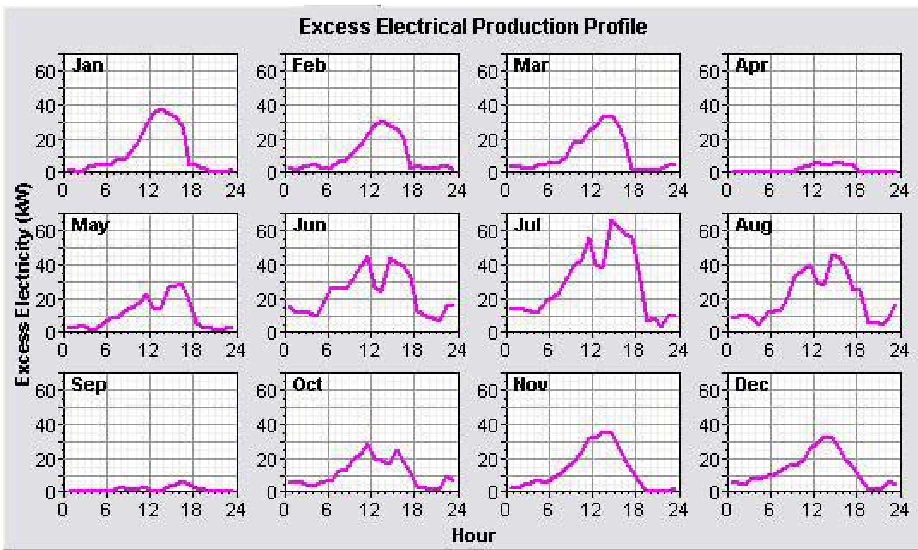


Figure3: Excess Electricity production profile from a wind-pv hybrid system in Kutubdia

Case 2: For Kuakata – a coastal Inland

Like Kutubdia, same analyses have been done for an important inland coastal location, Kuakata. Figure5 shows the detailed electricity production from a PV-Wind system for Kuakata and the amount of excess energy. Use of more excess energy available will make the useful cost of energy lower.

Table4: Same as table3 but output in HOMER for Kuakata, wind speed at 5.5m/s and without subsidy

PV (kW)	FL100	Gen1 (kW)	Batt.	Conv. (kW)	Initial Capital	Total NPC	COE BDT/kWh	Ren. Frac.	Capacity Shortage
	1	30	660	70	20,353,556	31,293,898	15.955	0.87	0.05
10	1	30	700	70	23,855,556	32,937,480	16.674	0.90	0.04
	1	60			14,088,889	40,957,060	20.396	0.73	0.03
10		65	280	40	7,546,778	42,792,580	21.890	0.10	0.05
10	1	60		30	18,065,554	44,554,204	22.187	0.74	0.03
80	1		620	60	43,287,112	45,753,420	23.305	1.00	0.05
10		65		30	5,154,445	46,608,728	23.842	0.09	0.05

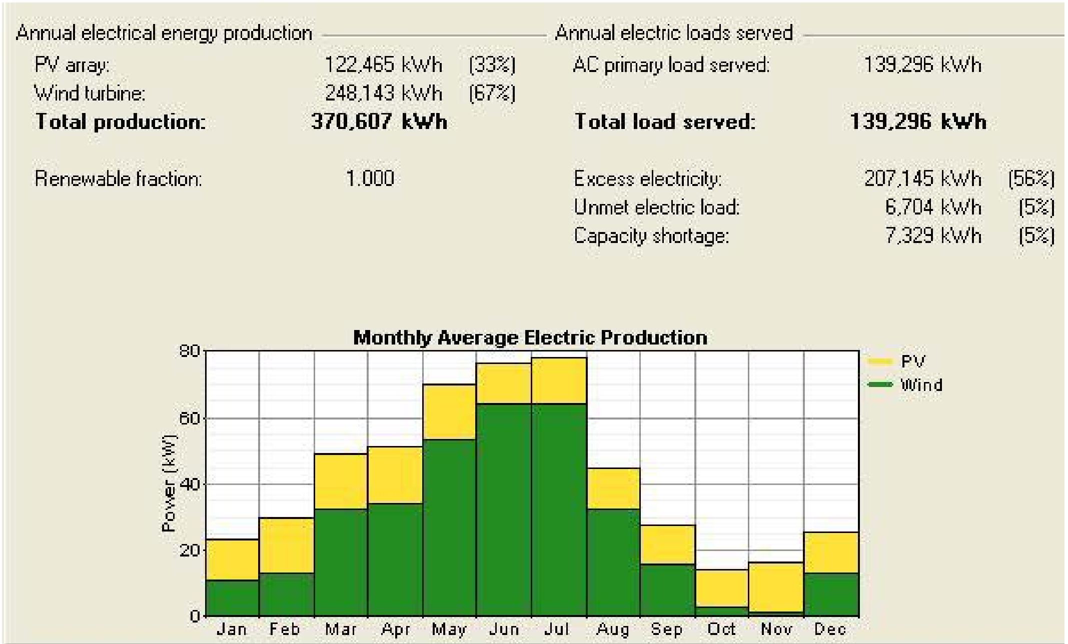
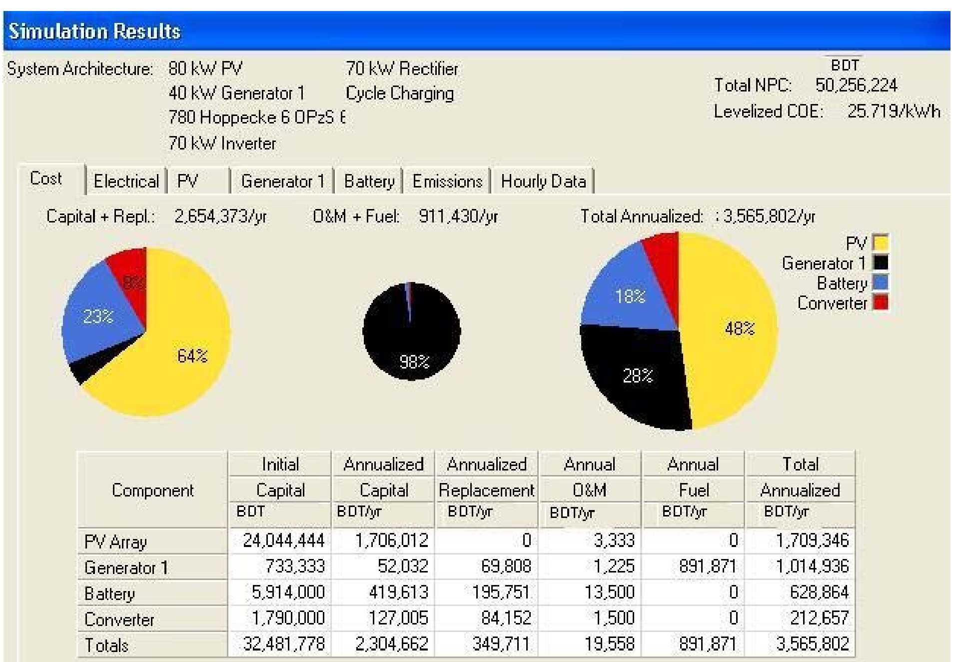


Figure5: Monthly Electric Production for Kuakata from a PV-Wind Energy system

Case3: For Rangpur

Rangpur is one of the important locations in the northern part of Bangladesh where different studies show that wind is not viable at all. Solar may be useful and therefore a PV-diesel system has been considered for the electricity generation. Figure6 shows the cost of the system and the useful cost of energy. Around 56% of the energy will come from solar and the rest from diesel.



Component	Initial Capital BDT	Annualized Capital BDT/yr	Annualized Replacement BDT/yr	Annual O&M BDT/yr	Annual Fuel BDT/yr	Total Annualized BDT/yr
PV Array	24,044,444	1,706,012	0	3,333	0	1,709,346
Generator 1	733,333	52,032	69,808	1,225	891,871	1,014,936
Battery	5,914,000	419,613	195,751	13,500	0	628,864
Converter	1,790,000	127,005	84,152	1,500	0	212,657
Totals	32,481,778	2,304,662	349,711	19,558	891,871	3,565,802

Figure6: Cost of different parameters for a 100kW PV-diesel system in Rangpur

Grid Connected System

As some of the coastal inland parts may be viable for wind energy generation and some of the northern parts are best for solar energy, therefore renewable based grid connected system for both of the locations have been analyzed.

Case4: Coastal Inland – Kuakata – Grid connected Wind Energy System

It has been found in the WAsP analysis and resource map developed by RISOE that some of the coastal inland parts may be suitable for small wind energy generation where wind power density is around 200 W/m^2. Therefore a simple analysis has been done for a grid connected wind energy system and table5 shows the results of that system.

Table5: Output of RETScreen for a 100kW Grid connected wind energy system where wind power density is around 200 W/m^2

Nearest location for weather data		Kuakata
Annual wind power density	W/m²	200
Height of wind power density	m	50.0
Wind plant capacity	kW	100
Gross energy production	MWh	169
Wind plant capacity factor	%	17%
Renewable energy delivered (Annually)	MWh	153
Net GHG Reduction (Base case – Diesel)	tCO2/yr	171
Initial Cost	BDT	**18,637,500**
Energy production cost	BDT/kWh	**5.14**

Energy production cost in table5 indicates that there should not have any doubt to connect the wind energy system to the national grid in Bangladesh. Figure7 also shows that even the system for the locations having 150 W/m^2 wind power density may be viable.

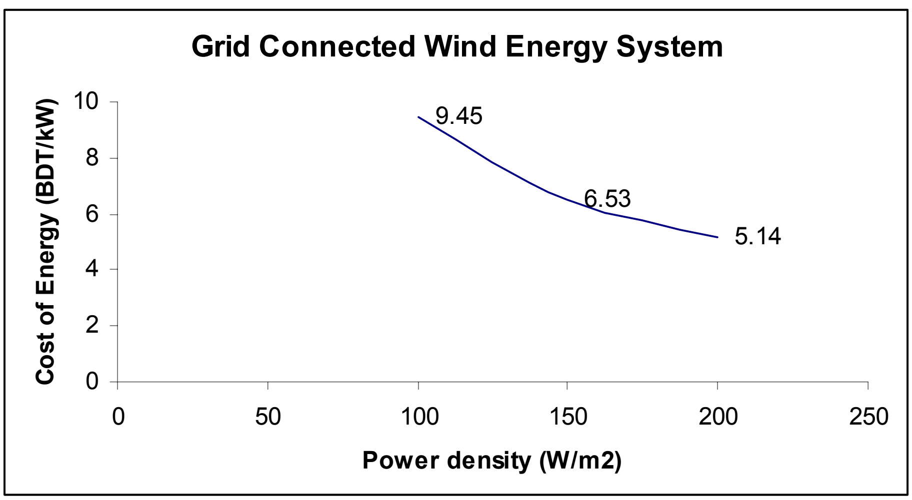


Figure7: Production Cost of Energy at different power density in the coastal part of Bangladesh

Case5: Northern part – Rajshahi – 100kW Grid connected Solar Energy System

Table6: Economic analysis of a 100kW grid connected PV system for Rajshahi

Grid type	-	Central-grid
PV energy absorption rate	%	100.0%
Overall PV system efficiency	%	12.3%
PV system capacity factor	%	16.8%
Renewable energy collected	MWh	156.287
Renewable energy delivered	MWh	**148.473**
	kWh	148,473
PV array area	m²	704.9
Initial Cost	BDT	**33,793,648**
Energy Production Cost	BDT/kWh	**09.68**
Net GHG Reduction (Base case – Diesel)	t_{CO2}/yr	164.84

Available solar energy for (8 + 40) degree combination – 1.72 MWh/m^2/year

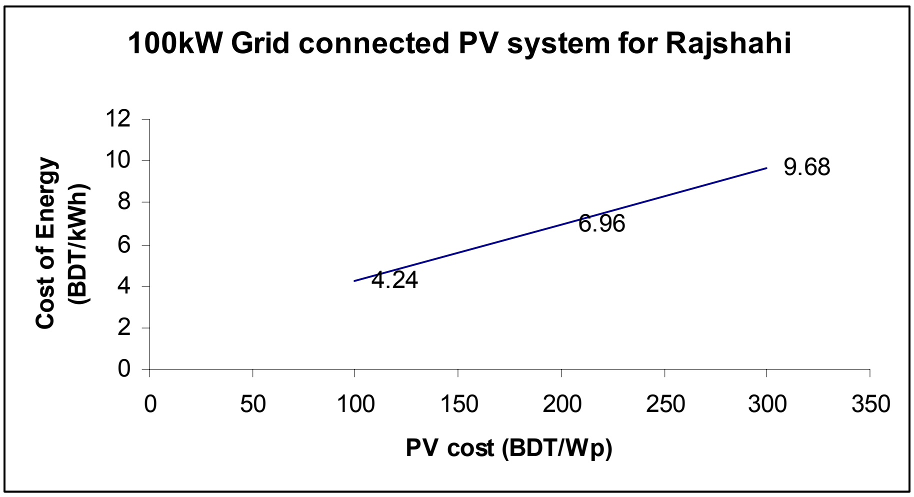


Figure8: Sensitivity analysis due to the change of PV cost for the grid connected system

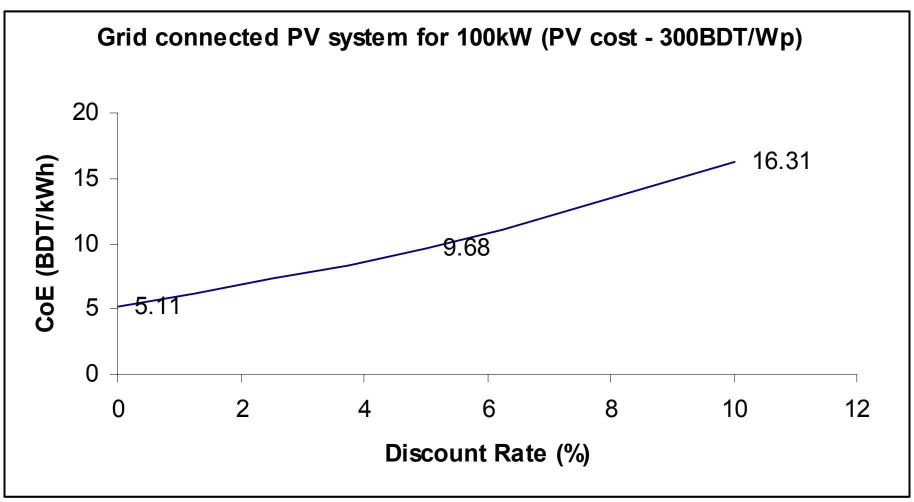


Figure9: Sensitivity analysis due to the change of discount rate for the grid connected system

Case6: Dhaka - Rooftop Grid Connected System

This case has been considered for Dhaka where a lot of tall apartments is building up day by day and the roof of that building can be used to generate electricity through PV to supply into the grid. Table 7 and 8 show the cost of production energy based on the present market cost of PV module and also the effect of PV module cost with discount rate for 10kW and 25kW systems.

It is to be mentioned that the first ever grid connected rooftop PV system in Bangladesh is being placed on the roof of RERC and now waiting for test to successfully run the system in Bangladeshi environment.

Table7: production cost of energy from a rooftop grid connected system for different PV module cost at Dhaka

	25kW	10kW
PV cost (BDT/Wp)	CoE (BDT/kWh)	CoE (BDT/kWh)
300	17.81	18.36
200	12.85	13.41
100	7.9	8.45

Table8: Sensitivity analysis due to the change of discount rate for rooftop grid connected PV system at Dhaka

For the system where PV cost is 300BDT/Wp		
Discount/Interest rate	25kW	10kW
	CoE (BDT/kWh)	CoE (BDT/kWh)
10	26.94	27.62
5	17.31	18.36
0	10.61	11.07

Annexure - A
Further information on energy scenario of Bangladesh

A 1. Energy Supply Sources:

Coal: Bangladesh began its first significant coal production in April 2003 with the opening of the Barapukuria Coal Mine in Dinajpur area of north-west Bangladesh with an estimated reserve of about 300 million tons. It is planned that 85% of its annual production of 1 million ton will be utilized to produce electricity, the rest will be used as fuel for brick making and other purposes. Extraction of coal from Phulbari deposits lying between 152m and 246m depth is yet to start. Feasibilities of mining from other deposits at lower depths have to be examined.

Oil: Bangladesh contains a small proven oil reserve of 56.9 million barrels and produces around 7000 barrels per day (bbl/d) of which 6000 bbl/d is crude oil.

Natural Gas: Natural gas is Bangladesh's only sizeable source of commercial energy with total production of 5.5 tcf. Estimates from Petrobangla put net reserves at 15.3 tcf as of mid-2004 (proven reserve is lower)

Hydro: At present only 230 MW of hydro power is utilized in Karnafuli Hydro Station, which is the only hydro-electric power plant operated by Bangladesh Power Development Board (BPDB). BPDB is considering extension of Karnafuli Hydro Station to add another 100 MW capacity. The additional energy will be generated during the rainy season when most of the water is spilled. Apart from Kaptai, two other prospective sites for hydro power generation at Sangu (100MW) and Matamuhuri (75MW) river are identified by BPDB. Small and micro hydro potential is around 200 MW. The total is 745 MW.

Traditional Biomass: Biomass is the most used energy source in Bangladesh which accounts for 67% of the total final energy consumption in Bangladesh. The main sources of biomass fuels are –

Trees (woodfuels, twigs, leaves, plant residues),
Agricultural Residues (paddy husk, bran, bagasse, jute stick etc.) and
Livestock (animal dung).

A 2. Energy Demand Scenarios

Two economic growth scenarios (Low Scenario and Reference Scenario) were considered to forecast future energy demands as presented in Tables1 & 2. Projected demands for commercial energy and electricity up to the year 2020 under both the scenarios are presented in tables below.

Table 1: Projected Demand for Energy (commercial and Electricity) under Low economic Growth Scenario (business as usual)

Year	1990	1995	2000	2005	2010	2015	2020
	Commercial Energy						
Population (million)	107	118	130	141	153	165	177
GNP Growth Rate (%)	4.44	5.25	5.24	5.24	5.24	6.65	6.65
Per capita GNP ($)	190	214	242	276	317	366	424

Energy Coefficient	1.62	1.37	1.37	1.37	1.08	1.08	1.08
Energy Growth Rate (%)	7.13	7.19	7.18	7.18	7.18	7.18	7.18
Per capita use (KgOE)	56	68	92	127	157	219	272
Total Energy (MTOE)	6	8	12	18	24	36	48
Total Energy (PJ)	256	342	512	769	1025	1537	2050
Energy Productivity (MJ/$GNP)	12.59	13.54	16.27	19.76	21.13	25.45	27.32
Electricity							
Status in Energy mix (%)	35	37	39	37	33	33	33
Total GWh	8205	11584	18315	26063	30994	46491	61988
Per capita kWh	77	98	141	185	203	282	351
Load factor (%)	55	57	57	57	58	59	60
Peak Load (MW)	1703	2320	3668	5220	6100	8995	11794

Table 2: Projected Demand for Energy (commercial and electricity) under Reference Economic Growth Scenario.

Year	1990	1995	2000	2005	2010	2015	2020
	Commercial Energy						
Population (million)	107	118	130	141	153	165	177
GNP Growth Rate (%)	4.5	5.4	6.4	7.2	7.7	8.2	8.7
Per capita GNP ($)	190	214	254	318	416	560	774
Energy Coefficient	1.62	1.37	1.37	1.37	1.8	1.08	1.08
Energy GrowthRate(%)	7.34	7.4	8.77	9.86	8.32	8.86	9.40
Per capita use (KgOE)	56	72	94	131	194	269	384
Total Energy (MTOE)	6	8	12	19	31	46	72
Total Energy (PJ)	256	362	531	827	1314	1979	3055
Energy Intensity (MJ/$GNP)	13	14	16	18	20	20	21
Electricity							
Status in Energy mix (%)	35	37	39	37	33	33	33
Total GWh	8207	12280	18971	28060	59858	46491	92402
Per capita kWh	77	104	146	185	363	282	523
Load factor (%)	55	57	57	57	59	59	60
Peak Load (MW)	1703	2459	3799	5220	11581	8995	17580

A 3. Rural electrification:

Rural electrification is a Constitutional commitment of Bangladesh Government. Till 1977 the Bangladesh Power Development Board was responsible for generation, transmission and distribution of electric power in Bangladesh and its main operational area was in suburban load centres. About 90% of the population in vast rural areas were practically without electricity. For the benefit of this vast rural people, REB was established through an Ordinance promulgated on 29th October 1977 and the Board started its operation from January 1, 1978. Functions of the Rural Electrification Board, as mentioned in the Ordinance, was to organise the prospective consumers of electricity of a selected area to form a Rural Electric Co-operative called Pally Bidyut Samity (PBS).

The profile of rural electrification is given below:

Area coverage / PBS	: Around 2000 Sq.Kms
No. of PBS	: 67
Number of villages energized	: 41,125
Number of 33/11KV Sub-station constructed	: 328
Length of power distribution lines	: 1,73,125 Km
Number of population in Programme Area	: 9,25,13,296
Category wise connection -	
Domestic	: 45,42,099
Commercial	: 6,06,666
Irrigation	: 1,38,869
Industry	: 95,059
Others	: 12,043
Total	: 53,94,736

A 4. Overview of IDCOL's Renewable Energy Programme

SHS is a convenient mode of supply power for small electrical loads such as lights, radio and black & white TV. This supply has proved to be reliable and the systems can be managed in rural areas with a little training. The main components of an SHS are a solar panel, a battery and a charge controller.

IDCOL undertook its solar program in January 2003 with the support from International Development Association (IDA) and Global Environmental Facility (GEF) to fulfill basic electricity requirements in the rural areas of Bangladesh. Under the program IDCOL intended to provide both grant and refinancing for 50,000 SHSs over a period of five-and-half years (January 2003-June 2008). The target was achieved in August 2006, three years ahead of the project completion period and US$2.0 million below estimated project cost of US$20 million. Therefore, the target was revised to finance a total of 200,000 SHSs by the year 2009 with additional support from the World Bank, GTZ and KfW.

Progress with SHS's installation up to 21 January 2007
PO wise installation of SHSs

Participating Organization	Number of SHSs Installed
Grameen Shakti	61,309
BRAC Foundation	22,115
Srizony Bangladesh	3,387
COAST Trust	1,270
TMSS	994
Centre for Mass Education and Science	1,263
Integrated Development Foundation	1,255
Shubashati	1,077
UBOMUS	1,620
BRIDGE	698
PMUK	61
RSF	1,600
PDBF	121
HF	139
Mukti Cox's Bazar	76
Other	77
Total	**97,062**

A good number of job opportunities, both for skilled and unskilled manpower, have been created. Specially, each unit office of Pos hires a local youth who has good knowledge about the area. It has paved the way for creating job opportunity locally. In addition, a good number of diploma engineers have been employed by POs to look after the technical aspects of SHS. Till March 2005, some 600 new jobs have been created by the program.

A5. R & D Activities on RET in different Organizations

Different Institutes, Universities and Research organizations (both public and private) are carrying out Research and Development (R&D) activities on diversified fields of renewable energy technologies. R&D activities of Bangladesh are characterized by plethora of constraints, including lack of expert manpower and financial resources. Different organizations and their field of interest related to R&D of RETs are presented in Table 3.

Table 3: Major R&D activities for RETs.

Technology	Major Organizations	Remarks
Solar Photovoltaic/ Balance of system	LGED, RERC, GS, CMES, BAU, BUET, Rahimafrooz, Micro Electronics, Energy Systems	Manufacture of all the balance of system components (like Charge controller, Cable, Battery, Inverter, Converter etc.) is made locally
Solar Water Heaters	RERC, BCSIR	Local design, fabrication and installation have been done
Improved Stoves	BCSIR, BRAC	Number of designs have been developed at BCSIR with three basic categories- (I) without chimney (II) with chimney and (III) with waste heat utilization.
Solar Cooker-Parabolic	BCSIR	BCSIR has successfully field-tested it's design which can quickly raise water to boiling point under clear sunny days.
Solar Cooker-Box Type	RERC, BCSIR, BRAC, CMES	The cooker is made of locally available raw materials.
Solar Dryer	RERC, BCSIR, BRRI, BAU	Different types have been designed and tested with locally available materials.
Solar Wood Seasoning Plant	BFRI	A simple, inexpensive and effective solar kiln has been developed.
Briquetting Machine	KUET, BRRI	Under the "RET in Asia" program, BIT Khulna is developing better machines with longer screw life.
Biogas	BCSIR, LGED, BAU, BRAC, GS	Fixed-Dome type plants are indigenously designed and constructed.

A 6a. Information about Hospitals in Bangladesh where SHS units may find use

Total No of Hospitals: 1383
Govt Hospitals: 671
No-Govt Hospitals: 712
Total beds in all hospitals: 46067
Total Beds in Govt Hospitals: 33828

A 6b. Information about handloom units where SHS units may find use

Total number of units: 2,12,481
Number of looms: 5,14,456

A 7. Present Energy Situation of the Coastal Areas

Energy users in the coastal region-whether households, commercial shops, small industries or community institutions-come across various problems. Most of the households do not have access to electricity as there is no power distribution network in the far-flung areas. Kerosene is the most common fuel used by the households for illumination purposes. Price of kerosene is often subject to fluctuations with the price going up in the event of scarcity of supply. The quality of light from kerosene lamps is poor and not adequate enough for all purposes. Besides, it pollutes the household environment through emission of smokes and is also hazardous. The households have to use dry cell for running different appliances like radio, emergency lighting. The price of such dry cell is relatively high. This causes extra financial burden to the household budget. In some areas there is scarcity of biomass-fuel which is used for cooking. The scarcity takes serious turn in the rainy season when procurement of biomass fuels becomes particularly difficult.

Some commercial shops located in market places treated as growth centres have some access to electricity. These market places are connected to the distribution networks of BPDB or PBS.

Small-scale private generators are in operation in some markets to provide electricity to the shops for limited hours, usually after the evening. The commercial shops in the non-electrified market places use kerosene lamps, candles, etc. which are not found suitable for their activities. The electrified shops faces the problems of load shedding, irregular supply of electricity and poor service by the utility agencies.

Most of the industrial units and irrigation pumps located in the far-flung coastal areas have no access to the grid-based supply of electricity. They are run by diesel, procurement of which is difficult. The diesel engine is reportedly subject to mechanical problems. The electrified industrial units suffer due to load shedding, non-cooperative attitude of the utility agencies and their poor service quality. Load shedding and frequent interruption in the supply of electricity affect the industrial units adversely causing a cut in production and revenue. The community institutions, especially the multi-purpose cyclone shelters having no access to electricity can not make optimum use of their infrastructural facilities.

A 8. Some Basic Profile of Six Coastal Islands

	Name of Upazila (District)	**Area** (Sq.km)	Population (in '000) (No. of households in 1991)	Estimated Population (1997)	Percentage of Literacy (7^+years) (1997)	Population **Density** per km (1997)
1.	Moheshkhali * (Cox's Bazar)	362	220 (33)	260	29.3	718
2.	Kutubdia (Cox's Bazar)	216	95 (14)	112	42.1	518
3.	Sandwip ** (Chittagong)	762	272 (45)	334	45.1	438
4.	Hatia *** (Noakhali)	1508	192 (48)	344	31.0	228

5.	Monpura (Bhola)	873	52 (9)	60	31.3	160
6.	Char Fasson (Bhola)	1106	342 (64)	392	38.8	354

* including Matarbari island
** including Urir Char island
*** including Nijhum Dwip island

A 9. Some Basic Profile of Six Selected Coastal Inland Location

	Name of Upazila (District)	Area (Sq.km)	Population (in'000) (No. of households in 1991)	Estimated Population (1997)	Percentage of Literacy (7^{+}years) 1997	Population Density per km (1997)
1.	Teknaf * (Cox's Bazar)	389	153 (24)	181	31.9	465
2.	Banshkhali (Chittagong)	377	321 (56)	388	29.1	1029
3.	Companyganj (Noakhali)	305	183 (31)	214	50.8	702
4.	Kalapara (Patuakhali)	483	175 (31)	197	42.7	408
5.	Patharghata (Barguna)	387	135 (26)	153	60.9	395
6.	Sarankhola (Bagerhat)	757	108 (20)	123	50.8	162**

* including St. Martin's Island
** density is low, as majority of the area fall under uninhabited Sundarbans

- National Population Density (1997) : 840
- Av. National Literacy : 39.0

A. 10: GHG Emission Factor

a) For Bangladesh fuel mixture for Grid electricity production according to RETScreen analysis is shown below:

Fuel type	Fuel mix	CO_2 emission factor	CH_4 emission factor	N_2O emission factor	Fuel conversion efficiency	GHG emission factor
	(%)	(kg/GJ)	(kg/GJ)	(kg/GJ)	(%)	(t_{CO2}/MWh)
Small hydro	4.9%	0.0	0.0000	0.0000	100.0%	0.000
Natural gas	90%	56.1	0.0030	0.0010	45.0%	0.452
Diesel (#2 oil)	5.1%	74.1	0.0020	0.0020	30.0%	0.897
Electricity mix	100.0%					0.452

Note: Global Warming Potential of GHG
1 ton CH_4 = 21 tons CO_2
1 ton N_2O = 310 tons CO_2

The GHG emission from electricity production of 20062MKWh in 2004 is 9million tons. The emission should increase with the years.

b) For Diesel Generators (Small)

Fuel type	Fuel mix	CO_2 emission factor	CH_4 emission factor	N_2O emission factor	Fuel conversion efficiency	GHG emission factor
	(%)	(kg/GJ)	(kg/GJ)	(kg/GJ)	(%)	(t_{CO2}/MWh)

Diesel (#2 oil)	100.0%	74.1	0.0020	0.0020	20.7%	1.301

Electricity generation using Diesel generators require costly fuel imports and produce a large amount of GHG emission. Hybrid units using wind or PV together with a smaller supply of diesel should reduce cost of import and GHG emission as well.

c) For Kerosene Lantern

Generally a Kerosene Lantern (equivalent to 5W electric lantern) requires 0.04 Litre Kerosene per hour. The emission from Kerosene is 2.58kgCO2/L. For each million homes in rural Bangladesh using two lanterns for three hours every night the emission is 0.2millions tons of CO_2.

A 11: GHG emission reduction:

a) Solar Home System (SHS)

A typical Solar Home System often consists of 4 fluorescent bulbs of 7W each, 1 B/W TV of 15W and a radio of 5W. Normally a home uses Kerosene for Lanterns and charges battery from grid supply at far away locations. This type of family can save 290 liters of kerosene per year by using solar lighting technology and can prevent the emission of 0.76 tons CO_2/year. In Bangladesh 65,000 number of SHSs have been installed and the number. will reach to 100,000 soon. Table 4 shows corresponding figures of saving kerosene and reducing CO_2 emission.

Table 4: CO_2 reduction using Solar Home System

Total no. SHSs	Savings of Kerosene in liters/year	tons CO_2/year
65,000	19 million	49,000
1,00,000	29 million	75,000

b) Market Electrification using SPV

If a community based rural market (50 shops and a 10W Florescent light each) replaces the diesel generator by SPV for lighting, then it can mitigate 1.1 ton of CO_2/year. In terms of kerosene as a base case, this is 19 tons of CO_2/year.

c) Solar Water Heating System(SWHS)

Solar Hot Water System to heat water form ambient temperature to 60^0 or above -can be used for heating or preheating in our country profitably. A SWHS of 500Litres/day can reduce 3.35 tCO_2/year (base case is Grid electricity).

A. 12. An Estimate of Financial requirements for immediate action

a) For continuation of solar and wind data recording and analysis by RERC to update and improve database.
Fund Requirement: $15,000 X 3years = $45,000

b) For feasibility studies which may be carried out by different organizations including RERC with technical help where necessary through TERI. These are in addition to demonstration activities carried on by LGED.

1. Water heating systems (500liters/day) in rural health clinics, rest houses, small hotels, multistoried buildings etc. For installation of five demonstration units:
Fund Requirement: $5,000 X 5 = $25,000

2. Large water heating systems for hospitals, hotels and industries.
   Pilot plant construction and installation cost: $30,000

3. Wind-diesel and Wind-PV systems 30KW in a coastal location or an island.
   Fund for installation of 1unit: $200,000

4. Solar Photovoltaic(PV) mini-grid installation(1KW).
   Total Cost: $10,000

5. Electricity generation(9 – 10 KW) from rice husk in rice mills.
   Fund for installation of one unit: $30,000

6. LED lights from Solar Photovoltaic module for low-income people. 6W module with 1-2W LED lights.
   Cost for production and distribution of 100 lamps: $10,000

7. Grid connected PV. 1KW for technical feasibility: $20,000

Total estimated fund requirement: $370,000

c) Feasibility study may be followed by electricity and heat generation for selected locations using solar and wind resources depending upon the availability of funds.

1. Indicative requirement of funds for wind-diesel system is shown below:

Table 5: Five year financial plan for wind-diesel system.

Year	No. of Units, Capacity addition(KW)	Annual energy production, MWh, (utilization 66%)	Total NPC (000,USD)
2006-07	5 (150)	358	620
2007-08	10 (300)	717	1240
2008-09	20 (600)	1434	2480
2009-2010	50 (1500)	3585	6200
Total	**85 (1200)**	**6094**	**10540**

- NPC – Net Present Cost, required for total system installation

2. Solar heating systems (500LPD) may be marketed with a subsidy. Indicative subsidy requirement is shown in table below:

Table 6: subsidy requirement for SWHS (500 LPD capacity)

Year	No of Systems, capacity (LPD)	Subsidy (USD) / SWHS	Total Subsidy (USD)
2006-07	50 (25,000)	450	22500
2007-08	100 (50,000)	400	40000
2008-09	100 (50,000)	300	30000
2009-2010	100 (50,000)	200	20000
Total (4 years)	**350 (175,000)**		**112,500**

Annexure - B

KAMM/WAsP Numerical Wind Atlas Study for Bangladesh

(Prepared by Dr. Jake Badger, RISOE)

Introduction

The conventional method used to produce estimates of wind resource over large areas or regions, such as on a national scale, is to analyse wind measurements made at a number of sites around the region, as in for example the European Wind Atlas (Troen and Petersen, 1989). In order for this method to work well there needs to be a sufficient quantity of high quality data, covering the country. This criterion is sometimes difficult to satisfy and therefore other methods are required – methods that will not meet bankable accuracy in resource estimates, but on the other hand that will typically give good indications of the geographical distribution of the wind resource and as such will be very useful for decision making and planning of feasibility studies.

Numerical wind atlas methodologies have been devised to solve the issue of insufficient wind measurements. One such methodology is the KAMM/WAsP method developed at Risø National Laboratory (Frank and Landberg, 1997). In this methodology an approach called **statistical-dynamical downscaling** is used (Frey-Buness et al, 1995). The basis for the method is that there is a robust relationship between meteorological situations at the large-scale and meteorological situations at the small-scale.

Information about the large-scale meteorological situation is freely available from the NCEP/NCAR reanalysis data-set. This data-set has been created by assimilating measurement data from around the globe in a consistent fashion from 1948 to the present day. The primary purpose for the generation of this data-set is to provide a reference for the state of the atmosphere and to identify any features of climate change. Another application of the data-set is as a long-term record of large-scale wind conditions. The NCEP/NCAR data is used to create around 100 different large-scale wind situations, called wind classes that represent the large-scale wind climate.

In order to make these wind classes meaningful at a smaller scale a mesoscale model is used to find out how the large-scale wind forcing is modified by regional scale topography. Therefore for each wind class a mesoscale model simulation is performed using the Karlsruhe Atmospheric Mesoscale Model (KAMM, Adrian and Fiedler, 1991).

Post-processing of the results from all the simulations yields a wind resource map at the resolution of the model simulations. Further analysis of the results from the simulations with consideration to the topography as described in the mesoscale model, yields wind atlas maps for generalized surface conditions. Files containing detailed information about the wind speed and direction distributions can also be generated that are directly compatible with the WAsP software, the wind industry standard for site resource assessment calculations.

Model description

The Karlsruhe Atmospheric Mesoscale Model (KAMM) is a 3D, non-hydrostatic, and incompressible mesoscale model. It is described in Adrian and Fiedler (1991), and Adrian

(1994). Spatial derivatives are calculated in the model by central differences on a terrain following grid. The turbulent fluxes are modelled using a mixing-length model with stability dependent turbulent diffusion coefficients in stably stratified flow, and a non-local closure for the convective mixed layer. Lateral boundary conditions assume zero gradients normal to the inflow sides. On outflow boundaries, the horizontal equations of motion are replaced by a simple wave equation allowing signals to propagate out of the domain without reflection. Gravity waves can penetrate the upper boundary outward using the boundary condition of Klemp and Durran (1983).

KAMM is able to run as a “stand-alone” model, i.e. the model can be run by using only the large-scale forcing in the form of a single vertical profile of geostrophic wind and virtual potential temperature. Hence, it is not necessary to nest the mesoscale model within a larger model that must supply the boundary conditions. At regional scales the mesoscale model is used to model atmospheric flows in domains of 100-1000 km x 100-1000 km in size with a typical horizontal resolution of 5 km.

Figure 2 shows the modelling domain used for this numerical wind atlas study. It is 960 km x 960 km, which corresponds to 97 x 97 grid points at 10 km resolution. It is necessary for the domain to be this size in order to include the important topographical features that will impact the winds in the region of interest. The final choice of domain followed experiments examining the wind fields using various domains. It was found that the winds within Bangladesh are strongly influenced by the elevated terrain outside of the country to the north and to the east. Therefore a domain significantly larger than the country itself had to be used.

In the vertical the model extends from sea level to 9900 m above sea level, using 32 model levels employing a terrain following coordinate. The interval between vertical levels is not uniform. This allows for more closely spaced vertical model levels near to terrain. Above low lying land the first 5 model levels are at 0 m, ~30, ~80, ~150 and ~240 m above the surface. The separation between these levels is smaller in elevated terrain.

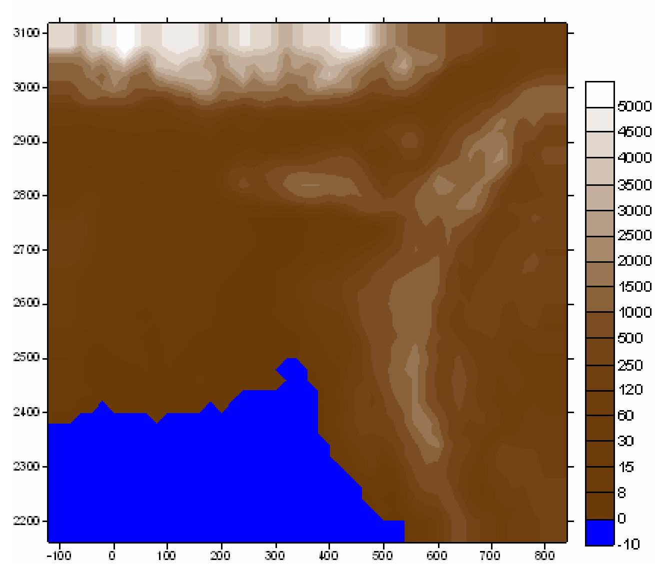


Figure 2: The surface elevation over the full computational domain used for the KAMM mesoscale modelling at 10 km resolution. The x and y axis are given in UTM (zone 46) coordinates in kilometres using datum WGS84.

Surface elevation data is derived from NASA's Shuttle Radar Topography Mission (STRM) dataset version 2. The dataset can be accessed via ftp://e0srp01u.ecs.nasa.gov. This data uses a longitude-latitude projection at 30 arc second resolution. This elevation data is manipulated first to change it to a UTM coordinate system and then to change the resolution appropriately for the mesoscale simulations. The surface elevation for the modelling domain is shown in Figure 2.

Aerodynamic surface roughness length data is derived from the United States Geological Survey (USGS) Global Land Cover Classification, also known as GLCC. The data can be accessed via http://edcsns17.cr.usgs.gov/glcc/. This data is given using the Lambert azimuthal projection. This land cover data is converted to UTM coordinate system and then to the appropriate resolution. It is also converted from land cover data to surface roughness data. This is done by using a look-up table that relates specific land cover classifications to specific surface roughness lengths. The surface roughness for the region of interest is shown in Figure 3.

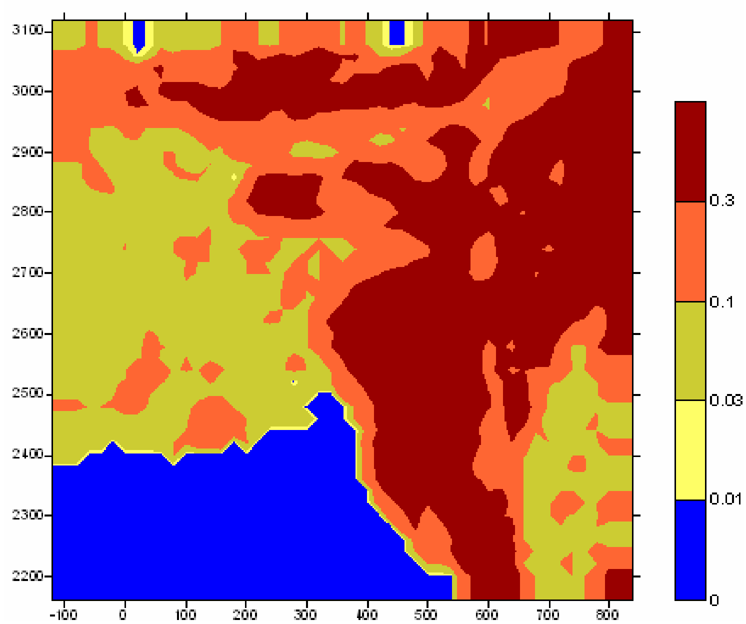


Figure 3: The surface aerodynamic roughness length for the full computational domain used for the KAMM mesoscale modelling at 10 km resolution. The x and y axis are given in UTM (zone 46) coordinates in kilometres using datum WGS84. The two low roughness areas at the northern boundary of the domain are due to snow and ice cover.

Large-scale Meteorological Conditions

The NCEP/NCAR reanalysis data for winds at 10 m above surface level have been used to assess the large-scale surface wind characteristics in the region of interest. The Climate Diagnostics Center provides access to the NCEP/NCAR reanalysis via http://www.cdc.noaa.gov/cdc/reanalysis/. Kalnay et al (1996) describes the NCEP/NCAR reanalysis project.

The 20-year annual and seasonal means for the 10 m winds are show in Figure 4 and Figure 5. In all the figures both the mean vector wind and mean absolute wind speed are plotted. It can be seen that large-scale surface winds are rather stronger in the coastal region of the country in the June-July-August (JJA) period, in which the monsoon flow is active, giving a southerly or south-westerly flow. An indication of the pre-monsoon flow is seen in the March-April-May (MAM) period plot, as the flow turns south-westerly after being weakly northerly during September-October-November and December-January-February periods. The large-scale flow away from the coastal region is weaker and has a more easterly component to it.

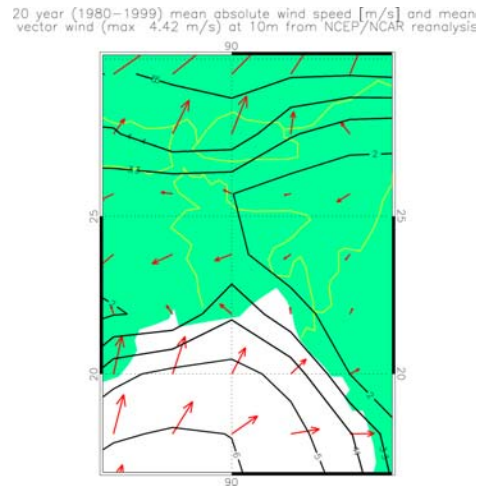


Figure 4: The 20-year mean wind at 10 m based on NCEP/NCAR reanalysis data from 1980-1999. The vectors show the mean vector wind and the contour lines show the mean absolute wind speed.

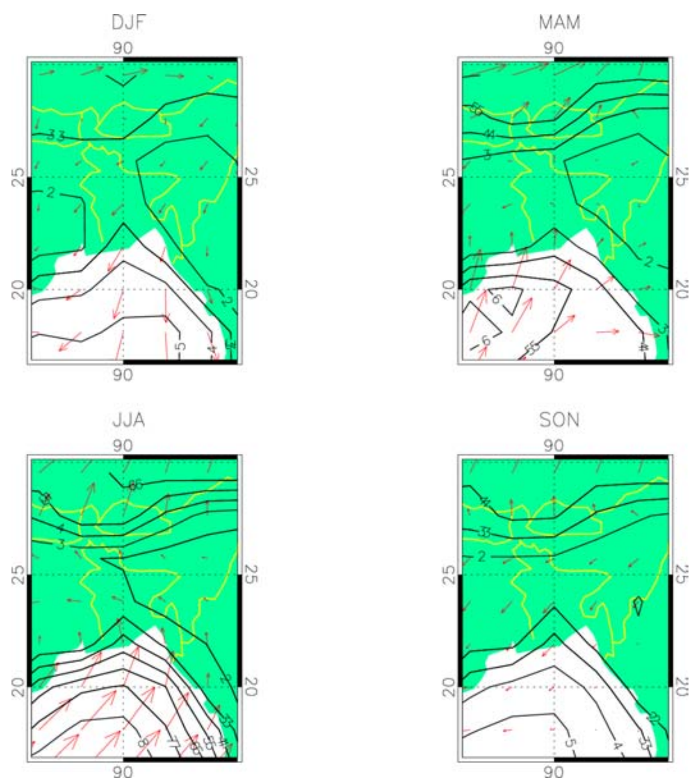


Figure 5: The 20-year seasonal mean winds; top-left December-January-February (DJF), top-right March-April-May (MAM), bottom-left June-July-August (JJA), and bottom-right September-October-

November (SON). The vectors show the mean vector wind and the contour lines show the mean absolute wind speed.

Initial Meteorological Data

Atmospheric data for the modelling initialization is obtained from the NCEP/NCAR reanalysis data-set on a longitude-latitude grid with a resolution of 2.5 x 2.5 degrees. Geopotential height data from 850, 700, 500, 300, and 200 hPa isobaric levels, temperature data from 850, 500, and 200 hPa isobaric levels, and humidity data from 850 and 500 hPa isobaric levels, are used. This data is converted into geostrophic wind and virtual potential temperature values for 100, 2000, 4000 and 9900 m heights above sea level. The data is compiled into 11-year time series, covering 1980 to 1990, for use in the wind class generation programs.

Classification system

The time-series data of wind and temperature profiles derived from NCEP/NCAR reanalysis data is used to determine 98 wind classes. These wind classes form a representative set of wind conditions for the region of interest. The wind classes represent different wind speed, wind directions, and atmospheric stability.

A way to assess the likely impact of an obstacle, such as a hill, on a flow is to calculate the Froude number. The Froude Number is U / (h * N), where U is the velocity scale, h is the height scale of obstacle, N^2 is the Brunt-Väisälä frequency, where $N^2 = (g/\theta_0)(d\theta/dz)$.

For cases where the Froude number is below one, the flow tends to flow around obstacles. For cases where the Froude number is above one, the flow tends to flow over obstacles. More stable conditions tend to lead to lower Froude number flow behaviour, in which channelling between or around obstacles is more prevalent, as well as lee effects to be more persistent.

The inverse Froude number squared is used in the wind class classification system to differentiate meteorological situations that have similar wind speed and direction but different thermal stratification. The height scale used is 1900 m, the height difference between the first and second level in the wind class profil

The result of the wind classification system was 98 vertical profiles of geostrophic wind speed, direction and potential temperature. KAMM uses profiles of the geostrophic wind to describe the large-scale forcings, this corresponds to prescribing large-scale horizontal pressure gradients present across the modelling domain. Away from the mid-latitudes the geostrophic wind becomes more of a notional wind than one that is closely realized in nature, however it still provides convenient way to describe a horizontal pressure gradient.

The wind classes used for this numerical wind atlas study are shown in Figure 6. The wind classes are based on the geostrophic wind at 91.25E 23.75N. The figure indicates the wind classes' wind speeds, directions and frequencies of occurrence. The frequency of occurrence shown in the figure is valid for the location 91.25E 23.75N. The frequencies of these wind classes are also calculated in the NCEP/NCAR grid locations in the vicinity of the region of interest. This is to account for the spatial variation of the large scale climate within the modelling domain, and is utilized in the construction of the wind climates, described in the next section.

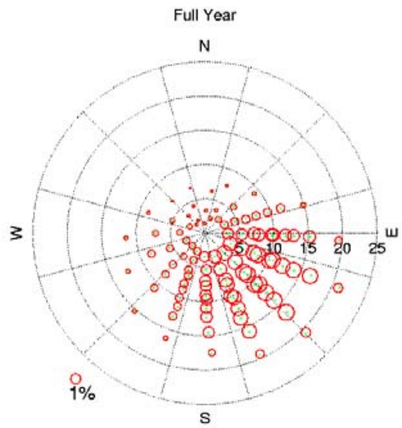


Figure 6: The geostrophic wind classes used as forcing for the simulations. Each circle represents a forcing wind speed (distance from the centre of the diagram) and direction. The speed scale is in m/s. The size of each circle represents the frequency of the wind class at the location 91.25E 23.75N. The symbol size corresponding to 1% frequency is given in the lower left hand corner.

Post-processing

After the mesoscale simulations for all of the wind classes are complete, the results are compiled in the post-processing stage of the methodology.

First, a weighted mean of the wind speeds at each mesoscale model grid point is calculated. The weightings for each wind class simulation are based on the frequencies of occurrence. The weightings for any given wind class vary over the mesoscale model grid points. This averaging operation yields a <u>simulated</u> resource map.

Second, for each wind class simulation, the effects of elevation and roughness variation are removed with modules similar to those in the WAsP software. Then the weighted mean of the adjusted result from the wind simulations is made. This yields a wind atlas map, or <u>generalized</u> wind map for flat surface condition of a specified roughness.
Figure 7 shows a schematic diagram of the wind class simulations and the post-processing steps.

Results

The results from the numerical wind atlas study using the KAMM/WAsP methodology can be output and utilized in two rather different ways. One way is to present the results in the form of resource maps, created in the method described above. These maps provide a good means to summarize the large amount of data generated in the study.

Another way to output the results is in the form of WAsP generalized wind climate files, known as *.lib-files*, because the convention is to use the extension '.lib' in their filename.

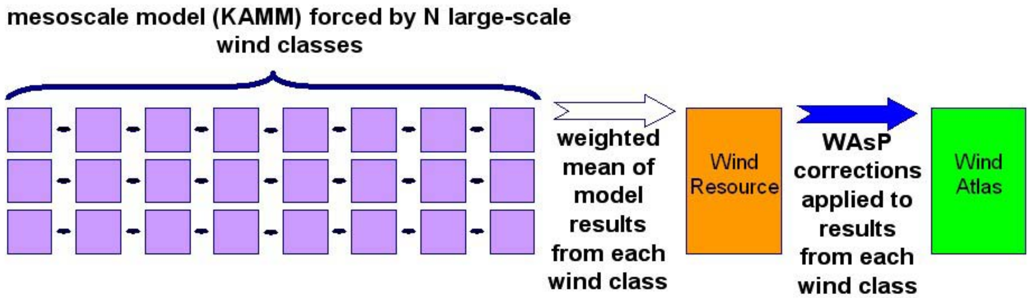


Figure 7. A schematic diagram showing the KAMM/WAsP numerical wind atlas methodology. In this numerical wind atlas study, N, the number of wind classes is 98.

The WAsP generalized wind climate files can be generated by the KAMM/WAsP methodology. This means that comprehensive information concerning the wind speed and direction distribution for various heights above ground level and for various surface roughness lengths can be obtained for any location within the region of interest.

The *.lib-files* for a selection of measurement station locations are used for comparison purposes. The measurement stations were selected by considering the quality of the data and the set-up of the mast and anemometer. The following measurement stations were selected Charfassion (BCAS), Khepupara (BMD), Cox's Bazaar (BMD), Kutubdia (BMD), Kutubdia (BCAS), Kuakata (BCAS). BMD and BCAS refer to the operator of the stations, namely Bangladesh Meteorological Department or Bangladesh Centre for Advanced Studies.

The measurements of wind speed and direction, have been analysed using the WAsP software. The WAsP software uses details of the sounding surface elevation changes and surface roughness changes, given in the form of maps, to remove the local effect of the topography on the wind speed and direction at the measurement site. The result is the generalize wind atlas in the form of a *.lib-file.* The *.lib-files* created using measurement data and modelling data can be compared. The locations of these stations are shown in Figure 13.

Figure 8 to Figure 12 show comparisons between the wind direction distributions at the station locations derived from wind measurement and from the mesoscale modelling. The measurement data is collected over different time periods, however fair comparison with the modelling results can be achieved by recalculating modelled wind climates based on the wind class weighting evaluated over the relevant measurement periods. Mainly there is reasonable agreement between the direction distributions. The mesoscale modelling tends to give a more concentrated predominant wind direction than the distributions based on measurements. The predominant wind direction in the coastal region from the measurements is southerly or south-easterly and this is captured by the mesoscale modelling results. The examination of the large-scale flow indicated that the wind is also sometimes from the north. This is seen in the measured and mesoscale modelled wind direction distributions.

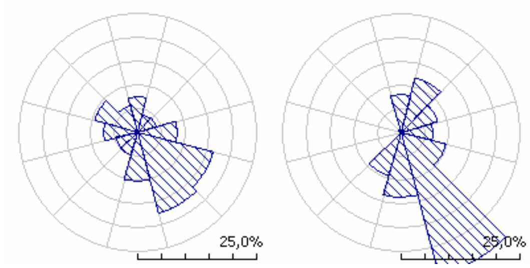


Figure 8: Wind direction distribution for Charfassion (BCAS) according to Measurement/WAsP (left) and KAMM/WAsP (right).

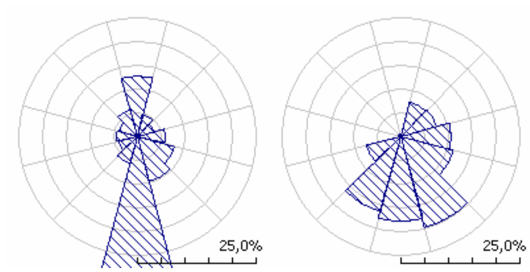


Figure 9: As Figure 8 but for Khepupara (BMD).

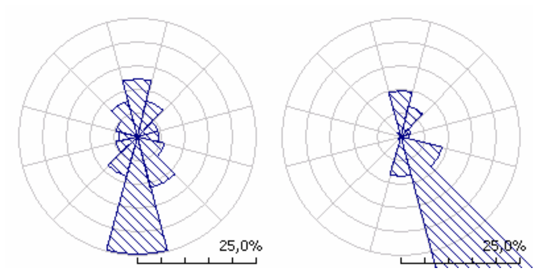


Figure 10: As Figure 8 but for Cox's Bazar (BMD).

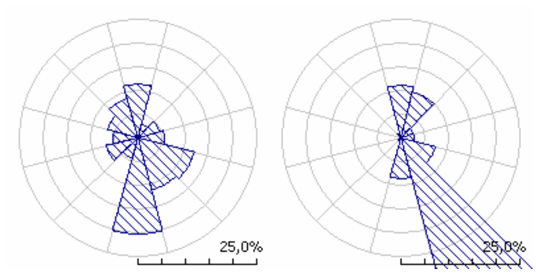


Figure 11: As Figure 8 but for Kutubdia (BMD).

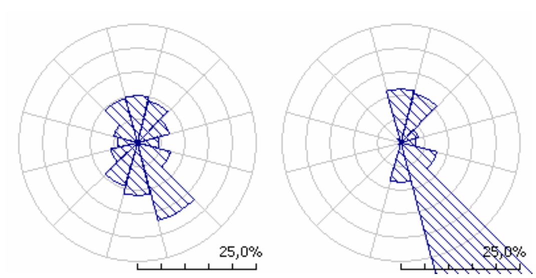


Figure 12: As Figure 8 but for Kutubdia (BCAS).

The modelling results suggest a more concentrated wind direction distribution for the stations closer to the elevated terrain in the eastern portion of the modelling domain. The elevated terrain running north to south acts to guide the flow in parallel to the elevated terrain, i.e. in the southerly or northerly direction.

However the measurements from the Khepupara station suggest a strong concentration of wind directions in the southerly or northerly directions that is not present to the same extent in the mesoscale modelling results.

Although the mesoscale modelling seems to have captured the measured wind direction distributions reasonably well it has been found that the wind speed distribution has been consistently underestimated in the mesoscale modelling. Due to time constraints it was decided that the best course of action was to perform an adjustment to the wind speeds through an adjustment of the wind speed distribution Weibull parameters, *A* and *k*,

$$A_{cor} = 1.28A$$
$$k_{cor} = \max(0.65k, 1.25) .$$

The first action of this correction is to enhance the wind speeds slightly and then to broaden the spread of the wind speed distribution.

The impact of the adjustment to the can be seen in Table 1 to Table 6, which give the wind speed distribution Weibull parameters, A and k, and the mean wind speed at 50 m a.g.l. above 0.03 m roughness length for the selected stations. In each table the first two rows give values derived from measures analysed in WAsP and KAMM/WAsP method. The last row in the table gives the adjusted values. The values in bracket are the percentage errors.

Before the adjustment is made there is a mean absolute error of 22% in the predicted wind speeds at the selected coastal station locations, compared to the WAsP analysis made. After the adjustment the mean absolute error is reduced to 8%. There is also a reduction in the power density estimate for the station locations to 31%.

Figure 13 shows the annual mean simulated wind for Bangladesh at 50 m above surface level. This map gives an overview impression of the variation of wind resources. However for any location on the map one would not expect necessarily to have measured the same mean wind speed indicated by the map. This is because the map has been created using a surface description at 10 km resolution. In reality the surface will be full of details in surface elevation and surface roughness. For example, small hills and forests, pertaining to elevation and surface roughness details respectively, will not be resolved.

The problem, created by the limit in the surface description resolution, impacts all numerical wind atlas methodologies. However the KAMM/WAsP method, because of the *.lib-files* creation feature, allows detailed information about the surface elevation and roughness at a site of interest to be added using the WAsP software.

Figure 14 shows the annual mean generalized wind climate. This map shows the resource when the effects of resolved surface elevation and roughness change are removed. It shows what the annual mean wind speed would be at 50 m above surface level for flat terrain with a uniform roughness of 3 cm. This map is useful because it shows the mesoscale influence on wind resource, i.e. variation of resource due to phenomena other than local orographic speed-up and roughness change.

Figure 15 and Figure 16, show the 50 m above surface level simulated and generalized mean power density respectively. The mean generalized power density map uses the same standard conditions as in the mean generalized wind speed map, namely flat terrain with a uniform roughness of 3 cm. These maps are more than simply a function of the mean wind speed cubed, because the mean power density is a function of the distribution of the wind speed.

	A [m/s]	K	U [m/s] (% error)
Measurement/WAsP	4.6	1.64	4.10
KAMM/WAsP orig.	3.8	2.35	3.41 (-17%)
KAMM/WAsP adj.	4.9	1.75	4.33 (+6%)

Table 1: Weibull parameters A and k for the Charfassion (BCAS) meteorological station.

	A [m/s]	K	U [m/s] (% error)
Measurement/WAsP	5.0	1.09	4.84
KAMM/WAsP orig.	3.9	2.35	3.43 (-29%)
KAMM/WAsP adj.	4.9	1.57	4.43 (-8%)

Table 2: Weibull parameters A and k for the Khepupara (BMD) meteorological station.

	A [m/s]	K	U [m/s] (% error)
Measurement/WAsP	4.3	1.42	3.88
KAMM/WAsP orig.	3.6	2.13	3.20 (-18%)
KAMM/WAsP adj.	4.6	1.66	4.07 (+5%)

Table 3: Weibull parameters A and k for the Cox's Bazar (BMD) meteorological station.

	A [m/s]	K	U [m/s] (% error)
Measurement/WAsP	4.8	1.24	4.48
KAMM/WAsP orig.	3.7	2.15	3.30 (-26%)
KAMM/WAsP adj.	4.7	1.70	4.17 (-7%)

Table 4: Weibull parameters A and k for the Kutubdia (BMD) meteorological station.

	A [m/s]	K	U [m/s] (% error)
Measurement/WAsP	5.3	1.76	4.71
KAMM/WAsP orig.	3.7	2.11	3.26 (-31%)
KAMM/WAsP adj.	4.6	1.66	4.13 (-12%)

Table 5: Weibull parameters A and k for the Kutubdia (BCAS) meteorological station.

	A [m/s]	K	U [m/s] (% error)
Measurement/WAsP	4.8	1.62	4.31
KAMM/WAsP orig.	4.1	2.39	3.63 (-16%)
KAMM/WAsP adj.	5.2	1.60	4.66 (8%)

Table 6: Weibull parameters A and k for the Kuakata (BCAS) meteorological station.

Error and uncertainty

Errors in the results from the KAMM/WAsP numerical wind atlas methodology may well stem from the imperfect representation of the large-scale forcings due to the limited number of wind classes that can be practicably used. Also the uncertainty associated with the NCEP/NCAR reanalysis profiles of geostrophic wind and potential temperature will be passed on through the process steps. Particularly in this region where there are high mountains to the north and east, stability plays a large role in determining how the flow interacts with the topography. The KAMM modelling assumes a uniform and steady atmospheric forcing, thus any wind features due to transient and spatially varying forcings are not accounted for well. Thermally driven winds, such as sea breezes, are known to be difficult to reproduce in the mesoscale model. Since the surface temperatures are uniform and held fixed it is expected that evolution of such wind phenomena are not very well reproduced.

Conclusions

In this chapter the application of the KAMM/WAsP numerical wind atlas method for the specified region of interest has been described. Maps of wind resource at 50 m have been produced. Data from *.lib-files* derived from measurement data and from modelling data have been compared for some coastal station locations. This has shown that the wind direction distribution is reasonably well reproduced, although the modelling results tend to show an exaggerated concentration of the prevailing wind directions. The atlas wind speed values tended to be underestimated by 22%, therefore an adjustment the wind speed distribution Weibull parameters, A and k, was carried out. This decreased the mean absolute error of the wind speed to 8 % from 22%. The mean absolute error of the predicted wind power density for the coastal stations was reduced to 30%. WAsP studies performed at locations away from the coastal region would be of great interest so that the numerical wind atlas can be evaluated in region not in the coastal zone.

References

Adrian, G, 1994. Zur Dynamik des Windfeldes über orographisch gegliedertem Gelände, Ber Deutschen Wettedienstes 188, Offenbach am Main 1994, 142 pp.

Adrian, G., F. Fiedler, 1991: Simulation of unstationary wind and temperature fields over complex terrain and comparison with observations. *Beitr. Phys. Atmosph*., 64:27-48

Frank, H. P., L. Landberg, 1997. Modelling the wind climate of Ireland. *Boundary-Layer Meteorology*, 85:359-378

Frank, H. P., O. Rathmann, N. G. Mortensen, L. Landberg, 2001: The Numerical Wind Atlas – the KAMM/WAsP Method, Risoe National Laboratory, Roskilde, Denmark. ISBN 87-550-2850-0, Risø-R-1252(EN).

Frey-Buness, F., D. Heimann, R. Sausen, 1995. A statistical-dynamical downscaling procedure for global climate simulations. *Theor. Appl. Climatol*., 50:117-131

Kalnay E, Kanamitsou M, Kistler R, Collins W, Deaven D, Gandin L, Irebell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Huggins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D, 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437-471

Klemp, J.B., D.R. Durran, 1983. An upper boundary condition permitting internal gravity wave radiation in numerical mesoscale models. Mon. Wea. Rev. 1983, 111, 430-444.

Troen, I., E. L. Petersen, 1989. European Wind Atlas. Risø National Laboratory for the Commission of the European Communities, Roskilde, Denmark, ISBN 87-550-1482-8.

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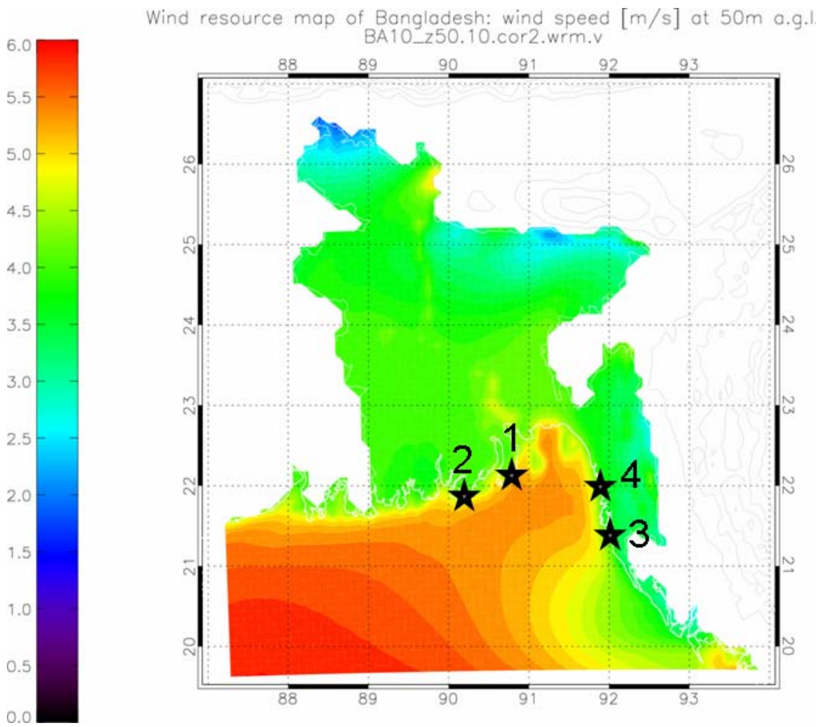

Figure 13: Annual mean <u>*simulated*</u> *wind speed at 50 m a.g.l.*

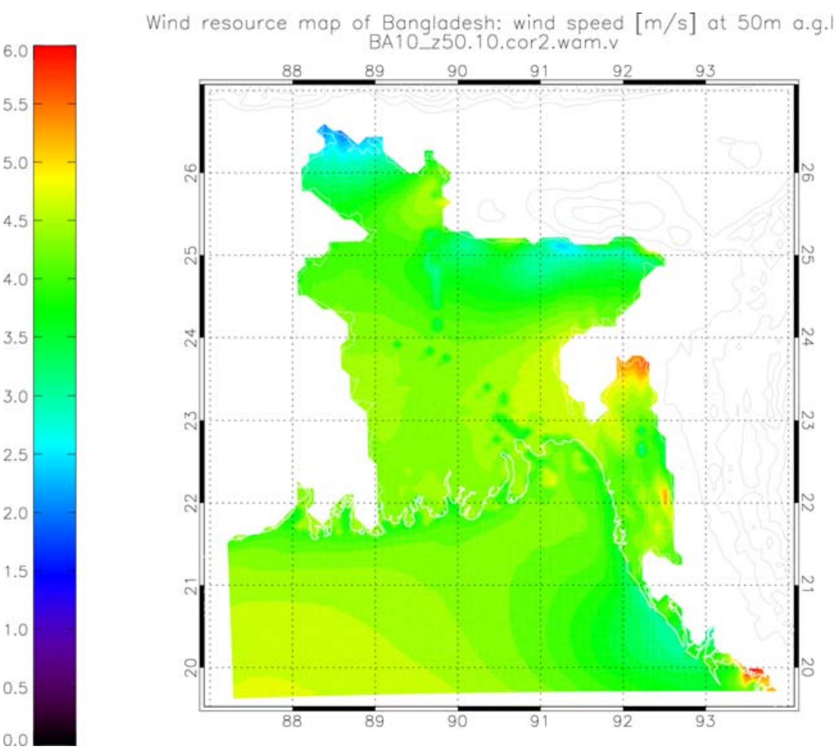

Figure 14: Annual mean <u>*generalized*</u> *wind speed at 50 m a.g.l. for 0.03 m roughness.*

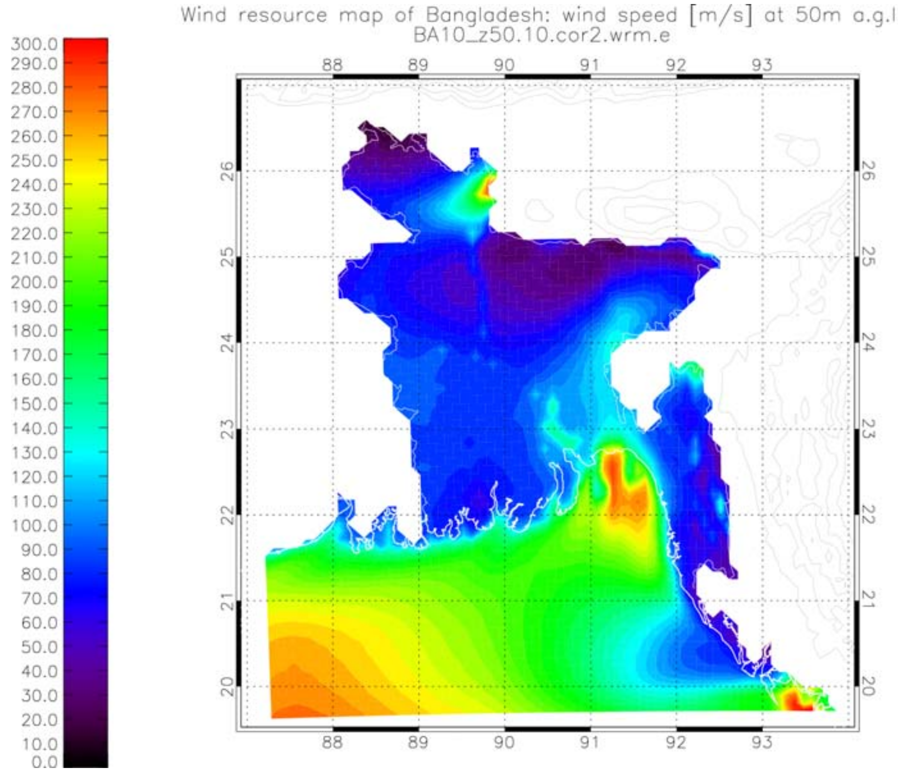

Figure 15: Annual mean *<u>simulated</u>* *wind power density at 50 m a.g.l.*

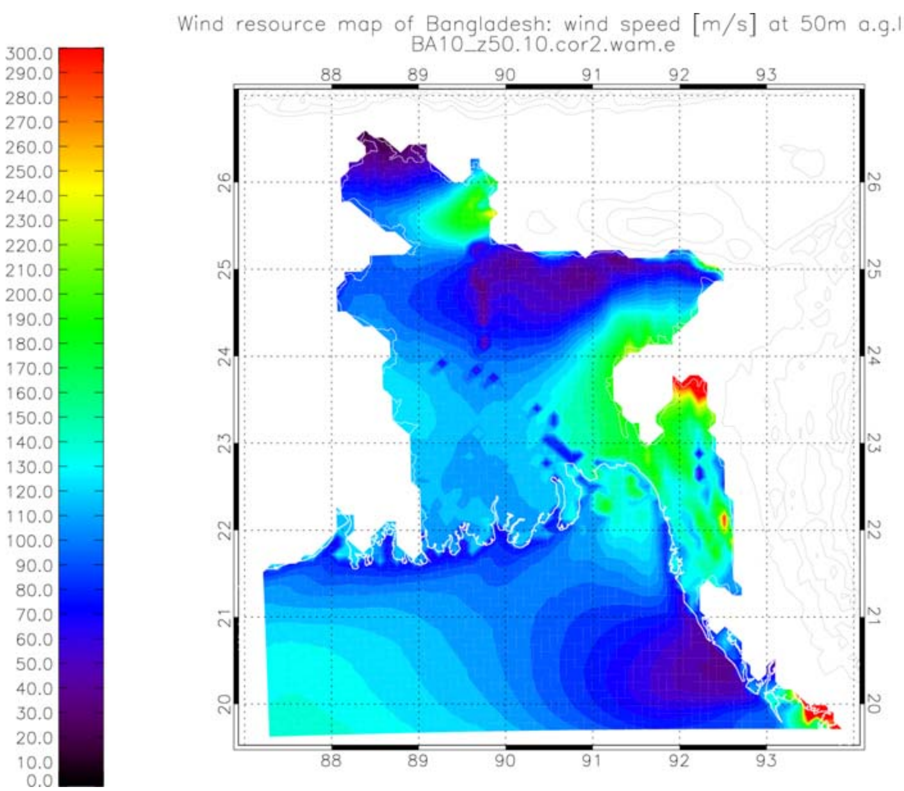

Figure 16: Annual mean *<u>generalized</u>* *wind power density at 50 m a.g.l. for 0.03 m roughnes*

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Assessment of Bangladesh Solar Resource

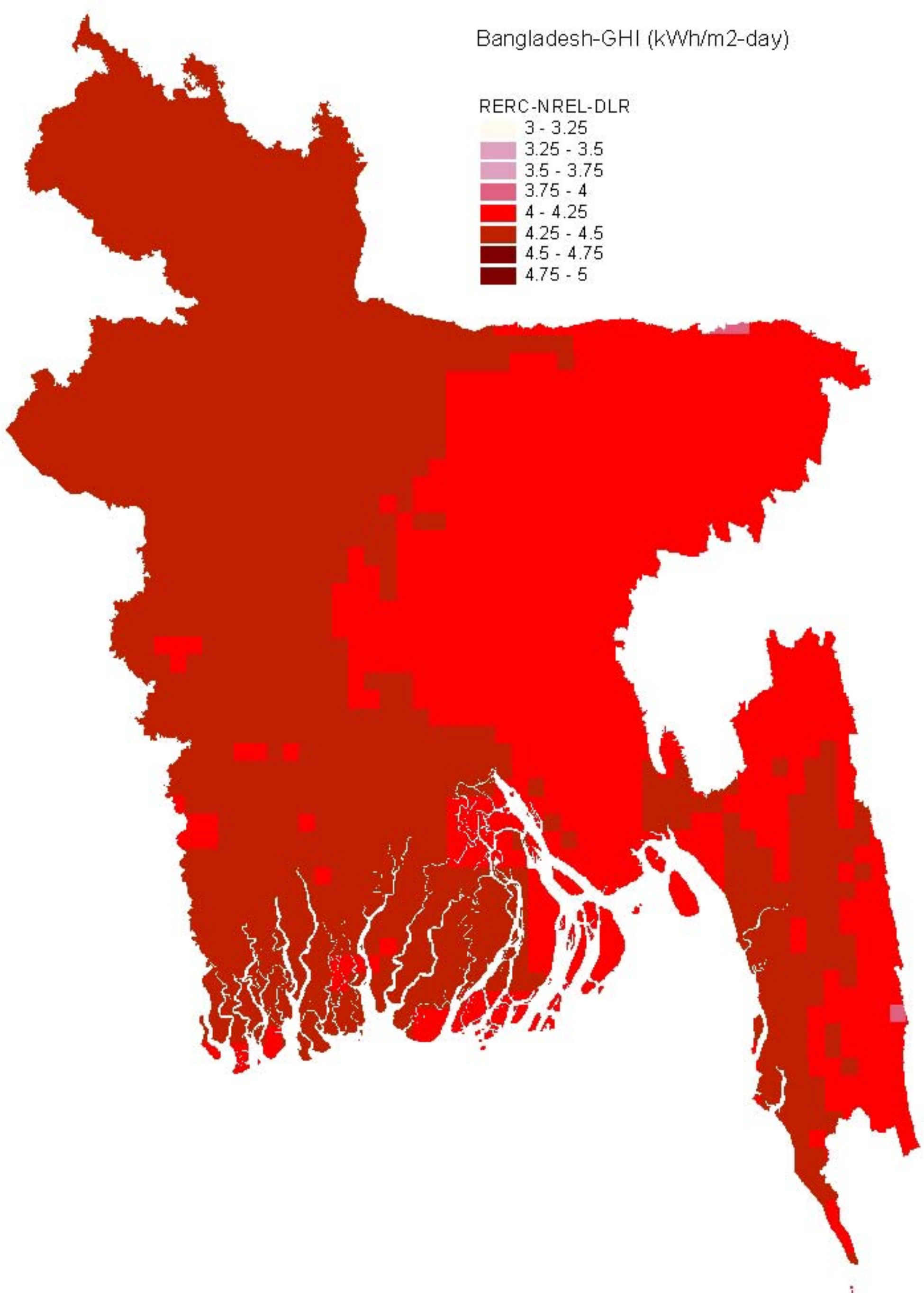

Fig 1: GHI map of RERC-NREL-DLR showing averaged NREL and DLR maps tuned to Dhaka

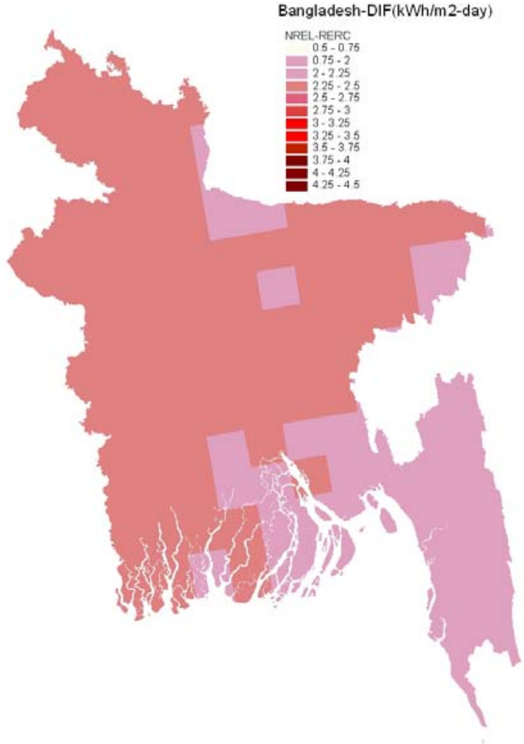

Figure 2: Annual DIF map of NREL tuned to Dhaka

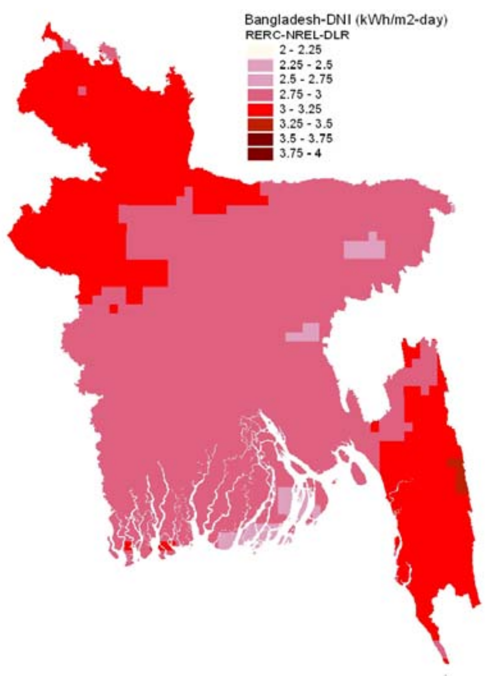

Fig 3: DNI map of RERC-NREL-DLR, showing averaged NREL and DLR maps tuned to Dhaka

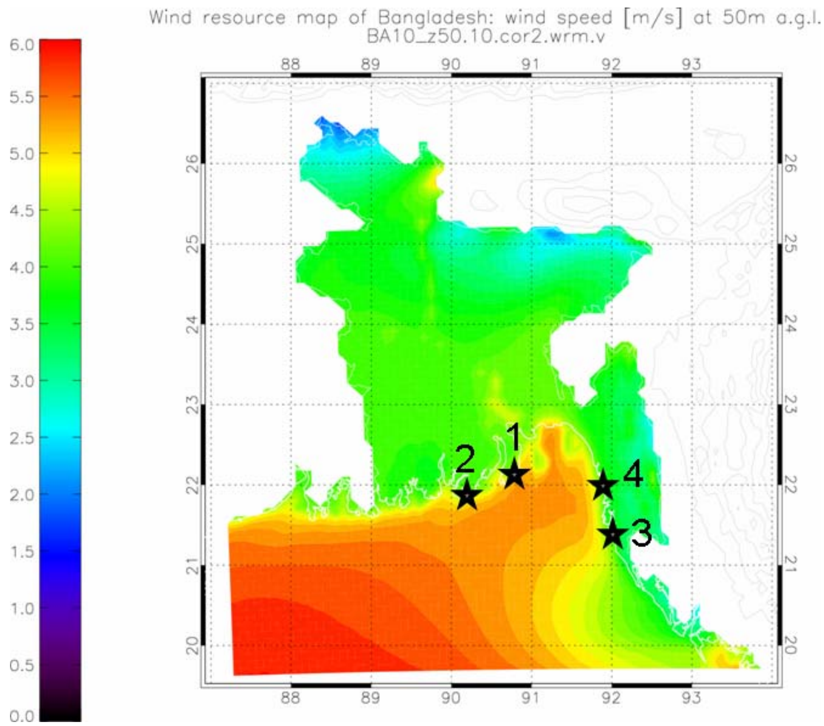

Figure 17: Annual mean simulated wind speed at 50 m a.g.l.

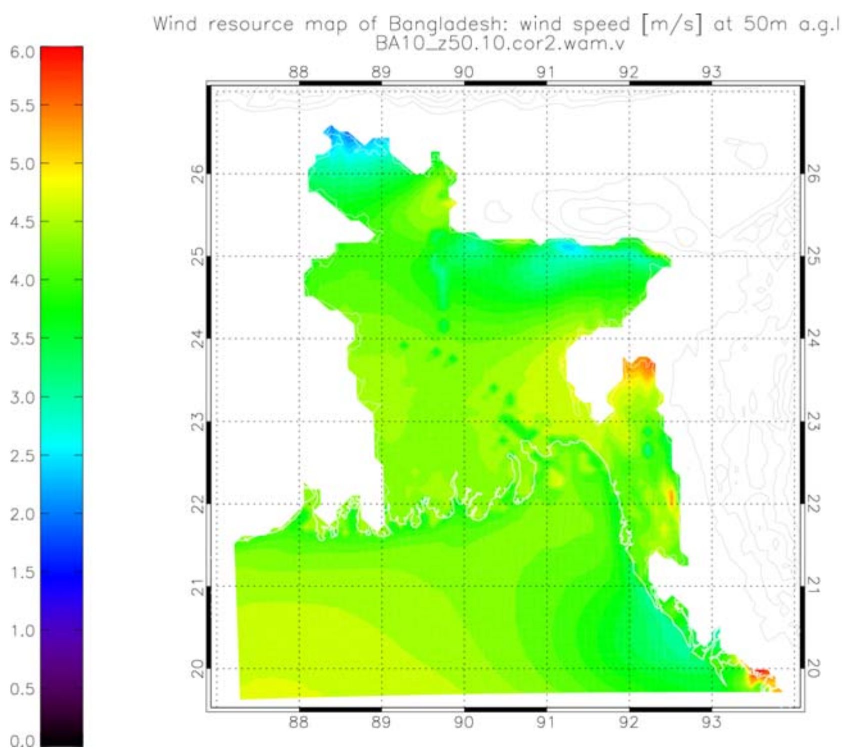

Figure 18: Annual mean generalized wind speed at 50 m a.g.l. for 0.03 m roughness.

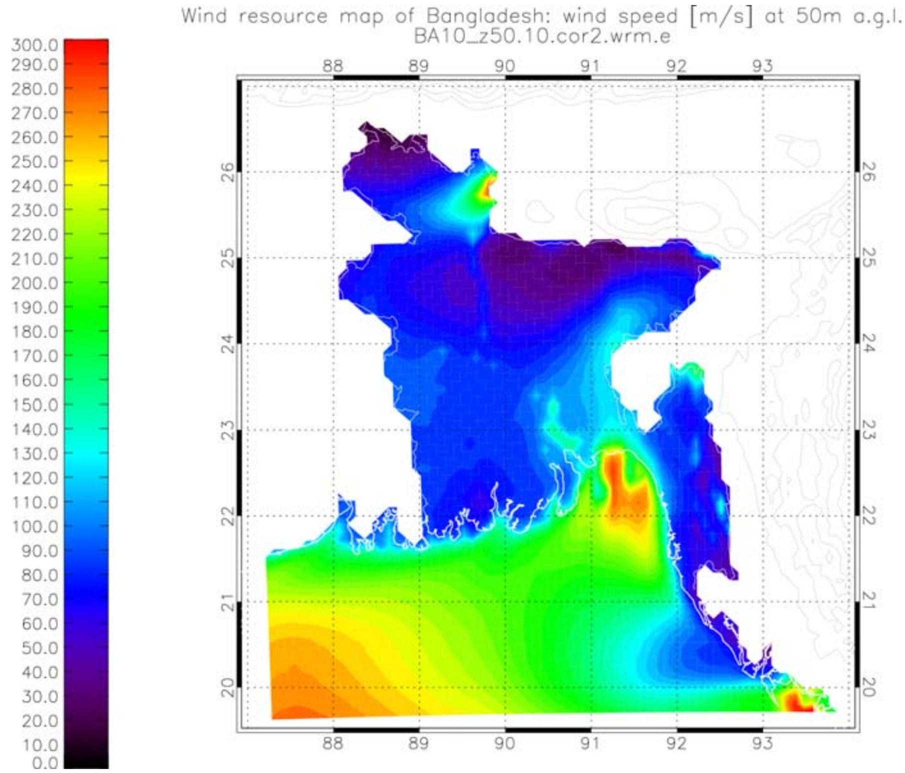

Figure 19: Annual mean simulated wind power density at 50 m a.g.l.

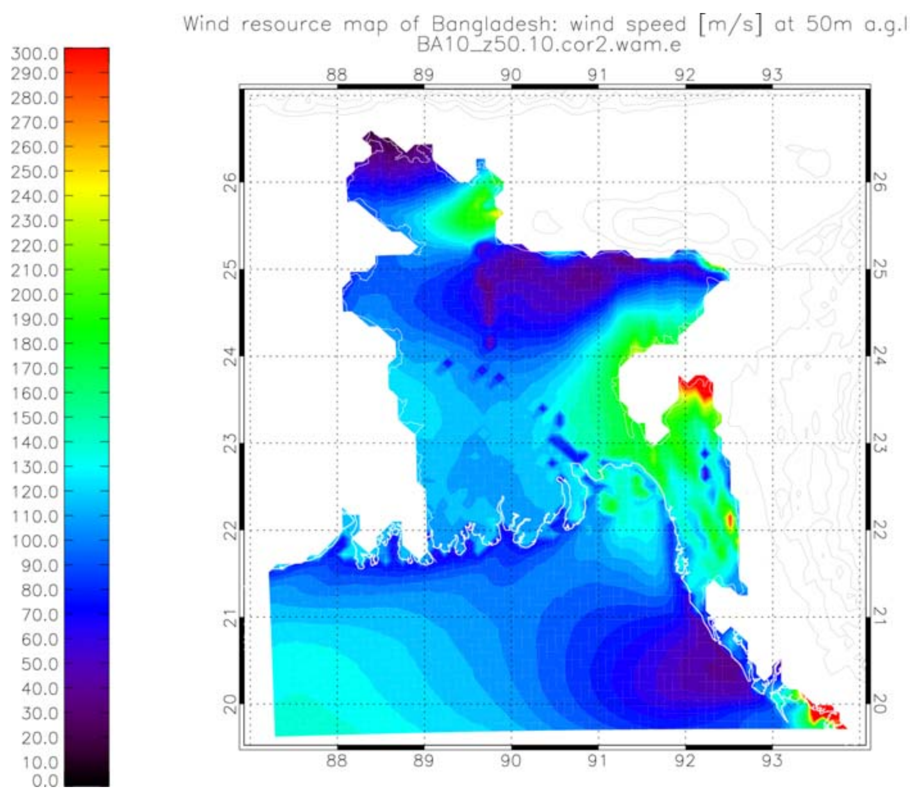

Figure 20: Annual mean generalized wind power density at 50 m a.g.l. for 0.03 m roughnes