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Prospects and Challenges of Decentralized Wind Applications in the Himalayan Terrain

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Abstract Wind energy has the potential to meet energy needs in remote areas. Exploitation of wind resource requires prospecting at the regional levels to assess the technical feasibility for small-scale wind applications. In situations of sparse primary data (surface wind), synthesised wind data based on prudent models are helpful. The current study focuses on the prospects of wind energy in the federal state of Himachal Pradesh, India, characterized by undulating terrain. Three synthesised wind data were collected based on physiographical understanding of the region and validated with long term surface wind measurements available for limited locations. The most representative synthesised wind data were re-validated using statistical methods and seasonal wind profiles were mapped through geospatial techniques. Variations of seasonal wind speeds in the region were consistent with surface measurements and highest range of 1~3.25 m/s was observed in the monsoon season. Large spatial influences of the elevation gradient were observed in the seasonal wind profiles. The high elevation zone (including Lahual Spiti, Kinnaur, Kullu and Shimla districts) in Himachal Pradesh have relatively higher wind speeds (> 2 m/s) during all seasons. These districts were identified as suitable candidates for detailed wind exploration. Wind potential in Himachal Pradesh is observed to be suitable for small-scale wind applications like low wind speed turbines, agricultural water pumps, wind-solar hybrids, space/water heaters, battery charging etc. Improvement in small-scale wind technologies will provide impetus to decentralize and cost effective solutions to meet energy demand in remote regions sustainably.

Keywords Renewable energy; Wind energy; Himalayas; Himachal Pradesh; Small wind

Introduction

Wind energy based electricity earned prominence in 19^{th} Century. This suffered a major setback with the highly subsidized fossil-fuel based centralized electricity generation and distribution. However, oil crisis of 1970's and elevated oil prices revived the global interest in wind based systems (Wise, 2000). India has installed over 14 gigawatt (GW) of wind power systems since then and stands fifth in the world (~200 GW) today. In the wake of climatic changes and perishing stock of fossil fuels, wind energy is being widely revered as a clean energy option of 21^{st} century that has high potential to offset carbon. It has been predicted that wind energy can produce 680 TWh of clean electricity globally in 2012, hence avoiding 408 million tons of CO_2 emissions. This also supports the clean development mechanism (CDM) endorsed by Kyoto Protocol (GWEC, 2012, http://gwec.net/wp-content/uploads/2012/06/IWEO_ 2011_ lo wres.pdf).

Nevertheless, major expanses of the world are still deemed as low wind potential areas, while energy demands are escalating. The overall wind potential in India is estimated to be 65 GW although there is enormous scope for up-scaling. Such low estimates are attributed to the wind resource assessment exercises that are performed with focus on large-scale wind turbines based on high winds. It has been argued that this trend towards large-scale wind technology and non-supportive policy intervention has curbed the development of small-scale wind technologies in certain parts of the world (Ross et al., 2012; Barry and Chapman, 2009). Proficient understanding of local wind dynamics with advancement in small-wind wind technologies gives stimulus to decentralize clean energy, particularly in remote areas with appreciable wind regimes (Nouni et al., 2007). This reiterates the need for detailed regional wind resource assessment exercises.

1 Regional wind resource assessment

Wind resource assessment is the primary step towards understanding the local wind dynamics of a region (Ramachandra et al., 1997). Wind flow developed due to the differential heating of earth is modified by its rotation and further influenced by local topography. This results in annual (year to year), seasonal, synoptic (passing weather), diurnal (day and night) and turbulent (second to second) changes in wind pattern (Hester and Harrison, 2003). Increased heat energy generated due to industries and escalating population in urban areas result in heat islands which affects the wind flow as well.

1.1 Surface wind measurements

Wind characteristics like speed and direction measured at meteorological stations (surface) aid in assessing the local wind resource. Wind patterns are observed to be tantamount for regions in proximity. However, local winds have high topographical and land cover influence, and assuming the wind data from a measured site applicable for a nearby site of interest calls for error. Monthly wind speed variation for regions within a radius of 30 km shows similar patterns but with difference in magnitude, and the study suggests using 6 years of long term wind data for satisfactory representation of monthly variations (Mani and Mooley, 1983). A one year wind speed data maintains an error within ± 10% which reduces to ± 3% for 3 years data but still burden the economics of a wind energy based project (European Wind Energy Association, 2012, http://www.wind-energy-the-facts.org/). The surface wind datasets sometime fail to capture the diurnal variations especially during the night hours, giving an elevated estimate of the daily average as wind speeds are generally higher in the daylight (Bekele and Palm, 2009). Despite these complexities, wind resource assessments based on the available surface measurements at different sites using statistical tools have provided satisfactory results (Ramachandra and Shruthi, 2003; Elamouri and Ben, 2008; Ullah et al., 2010, Dahmouni et al., 2011; Tiang and Ishak, 2012).

1.2 Models for prospecting wind

Surface wind measurements being reliable sources of information on the wind regime are available for only few locations. Acquiring surface wind data is expensive and time consuming. These gaps limit the wider spatial and temporal understanding of regional wind characteristics. In this regard, models like Wind Atlas Analysis and Application Program (WAsP) and Computational Fluid Dynamics (CFD) based on local topography and climate help in micro-scale (1~10 km) studies of wind resources. These models are validated with dense surface measurements and are not applicable for regions with thermally forced flows like sea breeze and mountain winds for which meso-scale (10~100 km) models are preferred. A combination of meso-scale and micro-scale models viz. the Karlsruhe Atmospheric Meso-scale Model (KAMM/WAsP), Meso Map and Windscape System along with geoinformatics provide reliable wind prospecting and have been tried for different regions (Coppin et al., 2012, http://www.csiro.au/files/files/pis7.pdf). However, these tools are expensive considering the scale of projects in small wind areas.

1.3 Synthesised wind data

Synthesised wind data available from various sources provide preliminary understanding of the wind regime of a region. Depending on the physiographical features and climatic conditions, these data help assess wind potential in the region of interest validated by long term surface wind measurements. Wind resource atlas derived with the help of National Oceanic and Atmospheric Administration (NOAA) and National Aeronautical and Space Agency (NASA) Surface Meteorology and Solar Energy (SSE) wind data, validated with available surface measurements, provided a range of mean wind speeds on a meso-scale wind atlas for Newfoundland (Khan and Iqbal, 2004). Similarly, a wind map for Bangladesh was prepared from synthesised global data of NOAA and NASA-SSE along with terrain specific surface features (Khan et al., 2004). Wind energy potential of the Saharan desert in Algeria was assessed based on NASA-SSE data and prospected to power a wind based desalination plant to support agriculture in the arid region (Mahmoudi et al., 2009). The application of NASA-SSE data for wind power prospecting in two islands of Fiji was also demonstrated (Kumar and Prasad, 2010). These studies substantiate the advantage and increasing interest in synthesized data for regional wind resource assessment.

The present study explores wind resource potential in Himachal Pradesh, a federal Indian state in Western Himalayas based on synthesised wind data, validated with surface measurements. Seasonal wind profiles showing spatial variation of wind speeds are developed using geospatial techniques. The discussion includes the scope for deploying small-scale wind applications suitable for meeting the local energy requirements.

2 Study areas

2.1 Landscape and climate

Himachal Pradesh is located between 30.38°~33.21° North latitudes and 75.77°~79.07° East longitudes, covering a geographical area of 55 673 km^2 with 12 districts (Government of Himachal Pradesh, http://hp planning.nic.in/statistics&data.htm). It has a complex terrain with elevation ranging from ~300 to 6 700 m as shown by the Digital Elevation Model (DEM) in Figure 1. Topography, climate, soil and vegetation clearly define the agro-climatic zones in the state. Parts of Una, Bilaspur, Hamirpur, Kangra, Solan and Sirmaur districts lower than 1 000 m above mean sea level represent the tropical zone. Certain segments of Solan, Sirmaur, Mandi, Chamba and Shimla districts located between 1 000~3 500 m have climate conditions varying from sub-tropical to wet-temperate. Lahaul Spiti, Kullu, Kinnaur and some parts of Shimla districts ranging between 3 500~6 700 m are part of the high elevation dry temperate, sub-alpine and alpine zones with sparse vegetation and rainfall.

2.2 Energy and environment

The hill state of Himachal Pradesh represents one of the rich biodiversity zones adversely impacted by unplanned development. Field investigations reveal substantially high energy requirement due to the colder climatic conditions, particularly in high elevation zone (>3 500 m). People are largely dependent on forests (fuelwood) for meeting their heating (room and water) and cooking demands, although vegetation cover is sparse in high elevation zone (Ramachandra et al., 2012). This has resulted in decline of vegetation cover, fragmentation of forests and associated ecological imbalance in an ecologically fragile region such as the Himalayas. In recent times, there has been increase in fossil-fuel based energy consumption, with resultant pollution and glacial melting (Aggarwal and Chandel, 2010). This necessitates exploration of clean renewable energy as decentralised sources. Even so, marginality and negligence of these mountain regions in the past have led to scarcity of reliable data which hinders efficient resource assessment and planning (Bhagat et al., 2006).

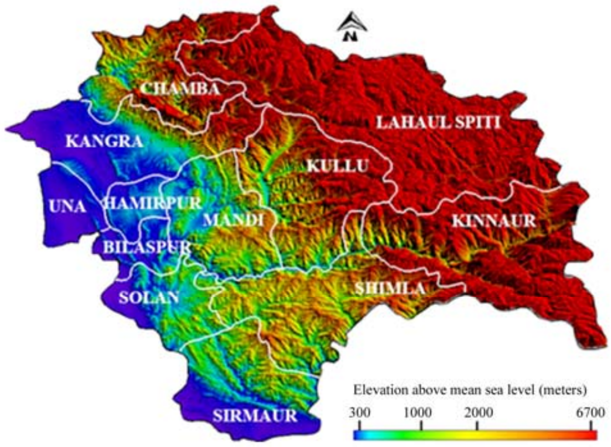

Figure 1 Digital elevation model (DEM) of Himachal Pradesh

3 Data, models and methods

3.1 Surface wind measurements

Long term wind characteristics in Himachal Pradesh were recorded at 13 meteorological stations (Figure 2) of the India Meteorological Department (IMD). Table 1 lists the IMD stations and periods of wind measurement exercises. Wind speed measurement heights varied from 1.7 m (Dalhousie), 5 m (Manali), 7 m (Dharmshala), 9.7 m (Bilaspur) to 26 m (Kyelong) and 26.5 m (Shimla).

Out of 13, IMD provided surface wind data for 10 stations (Bilaspur, Sundernagar, Nahan, Chamba, Bhuntar, Dharmshala, Dalhousie, Manali, Simla CPRI and Shimla) recorded for different durations (Table 1). Wind speed at Mandi was obtained from a literature on wind climatology in India (Mani and Mooley, 1983). The measured data included: 1) synoptic hour values (local time 8:30 and 17:30); 2) daily averages for durations between synoptic hours and; 3) monthly averages (not available for Mandi) of wind speeds. Daily averages of wind speeds were obtained by averaging the mean for two 12 hour periods starting from 17:30 hrs, capturing the diurnal variations of the wind. Wind measurements were standardized to 10 m using power law equation (1) as per World Meteorological Organization (WMO) norm (Ramachandra et al., 1997).

$$V/V_0 = (H/H_0)^{\alpha} \qquad (1)$$

where V_0 is the measured wind speed, V is the standardized wind speed, H_0 is the measured height, H is the desired height (10 m) and α is the power law index. Here α is a measure of roughness due to frictional and impact forces on the ground surface which varies according to terrain, time and seasons. The value of α calculated for most of the regions representing the Himalayan terrain are well above 0.40 based on long term observations and calculations (Mani and Mooley, 1983). In order to minimize extrapolation errors we considered the least value of 0.40 for Himachal Pradesh. The wind measurement heights in Himachal Pradesh were standardized using power law equation with α as 0.4.

Topography of Himachal Pradesh renders enormous variation to the micro-climate, wind speeds and direction, adding to complexity of wind resource assessment in the region. The available IMD surface wind data were characterized by large gaps and non-standard measurement heights. In addition, these stations were not representative of the diverse agroclimatic zones and particularly unavailable for the high elevation zone (> 3 500 m) of Himachal Pradesh (Figure 2). Capturing the wind regime of its complex terrain using these data cannot be a desirable option. Recently, IMD has deployed Automatic Weather Stations (AWS) at 22 locations in Himachal Pradesh (Figure 2) at 2 m heights above the ground (Automatic Weather Station, 2012, http://www.imdaws.com/). However, according to the communication from IMD, AWS based wind data were available merely for 3 stations (Bilaspur, Una and Udaipur) for the year 2011. Hence, we explored long term global wind datasets synthesised based on prudent models appropriate for the study area.

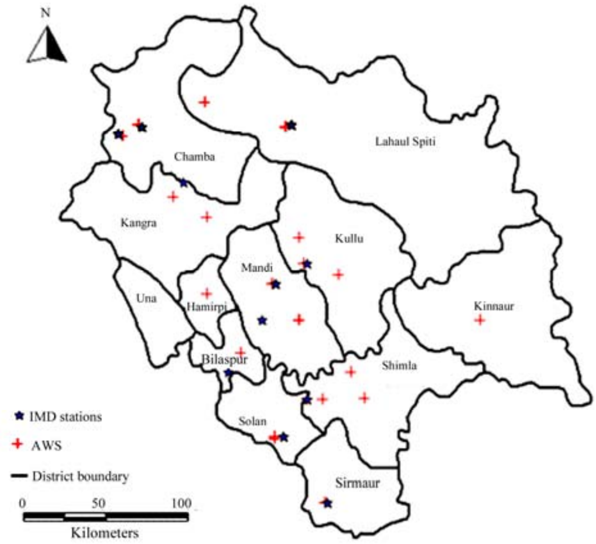

Figure 2 Total wind stations in Himachal Pradesh

3.2. Available synthesised wind data

3.2.1. NASA SSE

The National Aeronautics and Space Administration (NASA) Langley Research Center Surface Meteorology and Solar Energy (SSE) meteorological datasets were derived from a variety of earth-observing satellites. Particularly, NASA-SSE 10-year (1983~1993) monthly average wind speeds at 1°X1° spatial resolution for different heights above the earth's surface were developed based on a Global Circulation Model (GCM) applied on the outputs from Goddard Earth Observing System (GEOS). It is known that, vegetation and canopy reduces near-surface wind speeds variably. Hence, based on parameterizations developed from observations in Canada, Scandinavia, Africa, and South America, NASA synthesised wind speeds for 17 surface/vegetation types at different heights (Takacs et al., 1994; NASA, 2012, http://eosweb.larc.nasa.gov/sse/documents/SSE6Methodology.pdf).

According to NASA, synthesised SSE 10 m wind speed estimates for airport-like flat surfaces were validated with 30-year average airport wind data over the

Table 1 Long term wind measurement stations installed by IMD in Himachal Prades

Station	Long (E)	Latitude (N)	Elevation (m)	Wind data availability (period, source)
Nahan	76° 44'	30° 24'	959	1977-1998, IMD
Sundernagar	76° 88'	31° 53'	861	1981-1997, IMD
Chamba	76° 07'	32° 34'	996	1977-1990, IMD
Simla CPRI	77° 10'	31° 06'	2 202	1989-2003, IMD
Dalhousie	75° 58'	32° 32'	1 959	1951-1988, IMD
Dharmshala	76° 23'	32° 16'	1 211	1952-1998, IMD
Manali	77° 10'	32° 16'	2 039	1968-1998, IMD
Bilaspur	76° 40'	31° 15'	587	1956-1992, IMD
Bhuntar	77° 10'	31° 50'	1 096	1960-2003, IMD
Shimla	77° 10'	31° 06'	2 202	1933-1992, IMD
Kyelong	77° 04'	32° 35'	3 348+	1978, IMD
Mandi	76° 58'	31° 43'	761	1958-1967 (Ramachandra et al., 1997）
Dharmpur	77° 01'	30° 54'	1 986+	Period unknown, IMD

globe furnished by the RETScreen project. This had an estimated uncertainty of Root Mean Square (RMS) 1.3 m/s that is 20-25% relative to mean monthly values (NASA, 2012, http://eosweb.larc.nasa.gov/sse /documents/SSE6Methodology.pdf). However, studies have shown that NASA-SSE wind data exceeds the 25% error margin even in plain regions when compared to surface measurements (Kumar and Prasad, 2010). The SSE modelers agree that 1°×1° spatial resolution wind data is not an accurate predictor of local conditions in regions with significant topographic variation. The NASA-SSE wind speed data were accessed at http://eosweb.larc.nasa.gov/sse/.

3.2.2. NOAA-CIRES

The National Oceanic and Atmospheric Administration (NOAA) and University of Colorado CIRES Climate Diagnostics Center synthesised comprehensive global atmospheric circulation dataset as per their 20th Century Reanalysis project. NOAA-CIRES 20th Century Reanalysis Version 2 (Reanalysis is a scientific method for developing a comprehensive record of how weather and climate are changing over time wherein observations and a numerical model that simulates one or more aspects of the Earth system are combined objectively to generate a synthesized estimate of the state of the system (Reanalysis Intercomparison and Observations, 2012)). NOAA-CIRES 20th Century Reanalysis Version 2 dataset provides estimates of global tropospheric and stratospheric variability since 1871 at six-hourly temporal resolution. These were derived based on surface and sea level pressure measurements. Monthly sea-surface temperatures and sea-ice distributions were considered as boundary conditions in an Ensemble Kalman Filter data assimilation with support of certain parameterizations and global numerical weather prediction (NWP) model (NOAA, 2012, http://www.esrl.noaa.gov/psd/data/20thC_Rean/). The NWP model generates numerical simulations of the global atmospheric state, which are reanalysed and stored. However, NWP data are generally used as input of models which generate low resolution grids so as to infer the near-surface wind field. This process, called downscaling, is performed using statistical and dynamical considerations (Aguera-Perez et al., 2012). Global wind speeds of 138 years (1871~2008) at 2°×2° spatial resolution were accessed at http://www.esrl.noaa.gov/psd/data/20thC_Rean/.

3.2.3 CRU

Climate Research Unit (CRU) at the University of East Anglia maintains climatic average datasets of meteorological variables. This includes wind speeds for the period of 1961~1990 compiled from different sources with inter and intra variable consistency checks to minimize data consolidation errors. The Gobal Land One-km Base Elevation Project (GLOBE) data of the National Geophysical Data Center (NGDC) were re-sampled to 10’×10’ (ten minute spatial resolution) elevation grids where every cell with more than 25% land surface (those below 25% being considered water bodies) represents the average elevation of 100~400 GLOBE elevation points. The climatic average of wind speeds measured at 2 to 20 m anemometer heights (assumed to be standardized during collection) collated from 3 950 global meteorological stations together with the information on latitude, longitude and elevation were interpolated based on a geo-statistical technique called thin plate smoothing splines. Elevation as a co-predictor considers topographic influence on the wind speed and proximity of a region to the measuring station improves the reliability of the interpolated data. During interpolation inconsistent data were removed appropriately. This technique was identified to be steadfast in situations of data sparseness or irregularity (New et al., 2002). The 10’ ×10’ spatial resolution wind speed data as climatic averages were available for all global regions (excluding Antarctica). These were accessed at http://www.cru.uea.ac.uk/cru/data /hr g/tmc/.

3.3. Wind profiling

Synthesised wind speed data collected from NASA-SSE, NOAA-CIRES and CRU covering the study area of Himachal Pradesh grid-wise is represented in Figure 3 along with IMD surface measurement sites for which data were provided. Based on the spatial as well as ground (field visits) understanding of agroclimatic zones in Himachal Pradesh, 10 m surface/vegetation influenced wind speeds were collected from NASA-SSE for 14 grids (locations) at 1°×1° spatial resolution. These surface/vegetation types included: 1) rough glacial snow/ice (six locations above 3 500 m); 2) needleleaf-evergreen trees (three locations within 1 000-3 500 m) and; 3) broadleaf-needleleaf trees (five locations below 1 000 m). Similarly, 2°×2° coarse spatial resolution wind speeds for 9 grids and 10’ ×10’ high spatial resolution wind speeds for 266 grids were collected from NOAA-CIRES and CRU respectively (Figure 3). The collected wind speed data from NASA-SSE, NOAA-CIRES and CRU were interpolated using geospatial techniques to observe the annual wind speed regime over Himachal Pradesh. These data were validated and cross-compared with available surface wind speed measurements using statistical methods to identify the most representative data for the study area. Regional variations of this wind data were re-validated with surface measurement in proximity by generating buffers of 10 km around the IMD sites. Monthly average wind speed values from the representative synthesised data were used to produce seasonal wind profiles for Himachal Pradesh. These seasonal wind variations were compared with surface measurements from IMD.

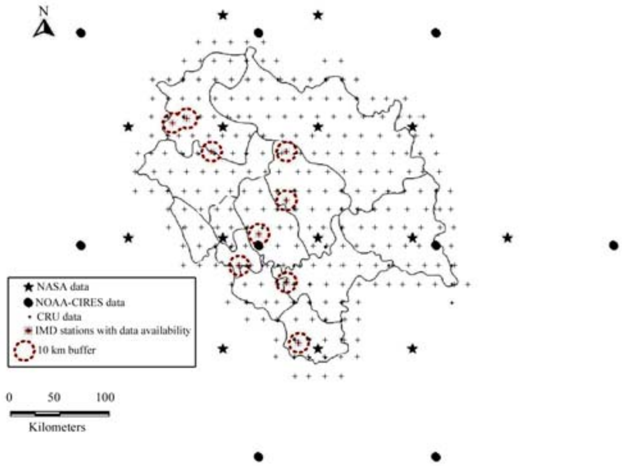

Figure 3 Synthesized as well as surface (IMD) wind speed locations for Himachal Pradesh

4 Results and Discussions

4.1 Representative synthesised wind data

Himachal Pradesh is a complex terrain with features like vegetation and local relief influencing wind speeds in the region. Wind regime represented by NASA-SSE data (Figure 4) varied from (2.14±0.42) to (4.45±0.48) m/s over the region. Long term but coarse NOAA-CIRES data (Figure 5) showed annual average wind speed variation similar to NASA-SSE, ranging from (1.96±0.73) to (4.29±0.70) m/s. High spatial resolution CRU wind speeds varied from (1.02±0.30) to (2.88±0.41) m/s (Figure 6). The three synthesised data, although different in magnitudes, showed a consistent increase in annual average wind speeds with increasing elevation that is also coherent with the agro-climate zones of Himachal Pradesh.

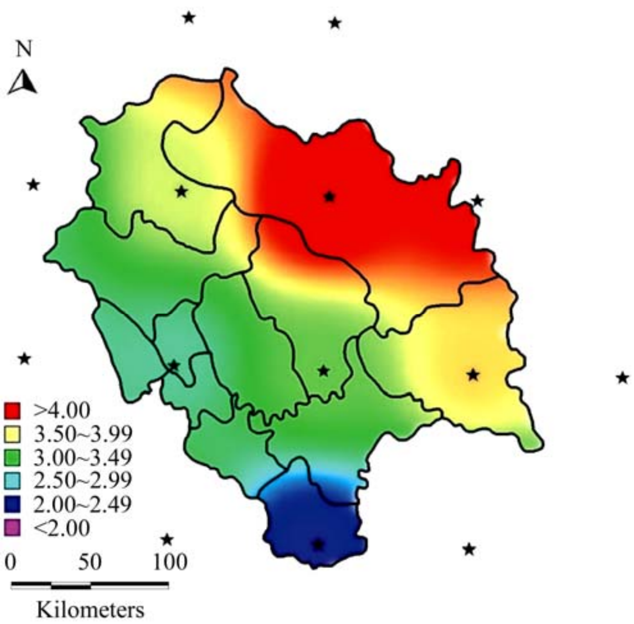

Figure 4 Annual average wind speed in Himachal Pradesh based on 1°×1°spatial resolution NASA-SSE data

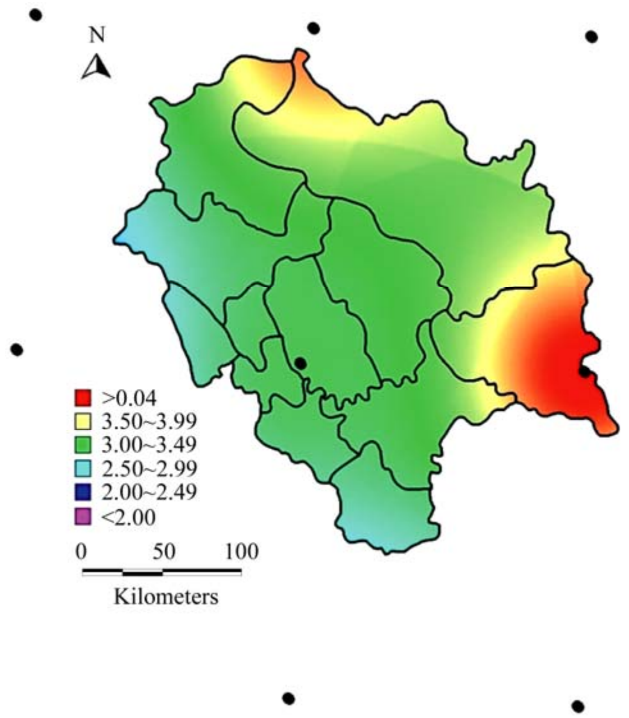

Figure 5 Annual average wind speed in Himachal Pradesh based on 2°×2° spatial resolution NOAA-CIRES reanalysis data

4.1.1 Validation

It is known that the density of vegetation and size of canopy cover reduces with increasing elevation (towards alpine zone) and facilitates higher wind flow. The surface measurements from IMD (though not representative of the entire state), validate the consistent increase in wind speeds with elevation as illustrated by the three synthesised data, viz. NASA-SSE, NOAA-CIRES and CRU (Figure 4~6).

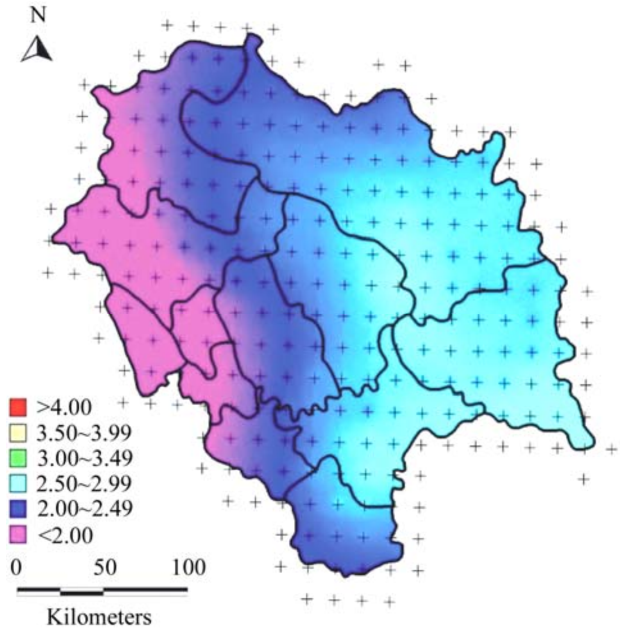

Figure 6 Annual average wind speed in Himachal Pradesh based on 10'×10' spatial resolution CRU data

Synthesised wind data were cross-compared using box-plots (Figure 7) to observe the pattern of monthly wind speed variations over the region. On comparison with NOAA-CIRES and CRU wind data, NASA-SSE values were observed to be exaggerated. Although, NOAA-CIRES data were more distributed due to their coarseness in spatial resolution, they showed similar monthly variations as CRU values, with a unimodal rise in wind speeds during monsoon season (June to September). Further, these data were validated with surface measurements of IMD. The RMSE (Root Mean Square Error) for NASA-SSE and NOAA-CIRES were 2.57 m/s and 1.92 m/s respectively. CRU data showed the least RMSE of 1.32 m/s on validation and hence scored over the rest as the most representative data for the region.

4.1.2 Re-validation

As discussed in section 1.1.1, wind patterns are retained within the vicinity of surface measurement sites even upto 30 km, even though magnitudes vary

Table 2 Correlation coefficients and interpretation (SAMHSA, 2011, http://pathwayscourses.samhsa.gov/eval201/eval201_ 4_ pg9. htm)

Correlation coefficient (r)	Strength of correlation	IMD sites considered for re-validating CRU data
0.90 - 1.00	Very high	Sundernagar
0.70 - 0.89	High	Bilaspur, Nahan, Bhuntar
0.40 - 0.69	Moderate	Chamba, Dharmshala, Dalhousie, Manali, Shimla CPRI
0.20 - 0.39	Low	-
0.00 - 0.19	Negligible	Shimla

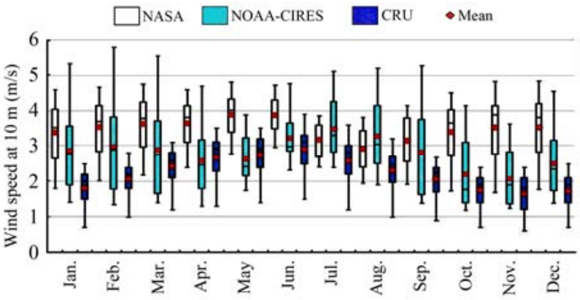

Figure 7 Cross-comparison of synthesised monthly wind speed data

(Mani and Mooley, 1983). For re-validation of the apparent representative wind data, CRU data within 10 km radius of ten IMD sites with surface data availability were considered (represented in Figure 3). CRU and IMD monthly wind speed values were compared for these sites using scatter plots (represented in Figure 8). Out of 10, 1 site (Sundernagar) showed very high, 3 sites (Bilaspur, Nahan, Bhuntar) showed high and 5 sites (Chamba, Dharmshala, Dalhousie, Manali, Shimla CPRI) showed moderate correlation between measured IMD and synthesised CRU values (Table 2). The undulating terrain of Himachal Pradesh renders variations in wind speeds even over small distances and hence explains the absolute lack of correlation between IMD and CRU values in Shimla.

The above findings reiterate that CRU wind speeds are the most representative among the three synthesised datasets collected. CRU model considers geographical influences and high resolution makes it prudent for meso-scale (10~100 km) seasonal wind profiling in the tough Himalayan terrain of Himachal Pradesh.

4.2 Seasonal wind profiling

Seasonal wind profiles for Himachal Pradesh based on CRU data were generated by Kriging interpolation

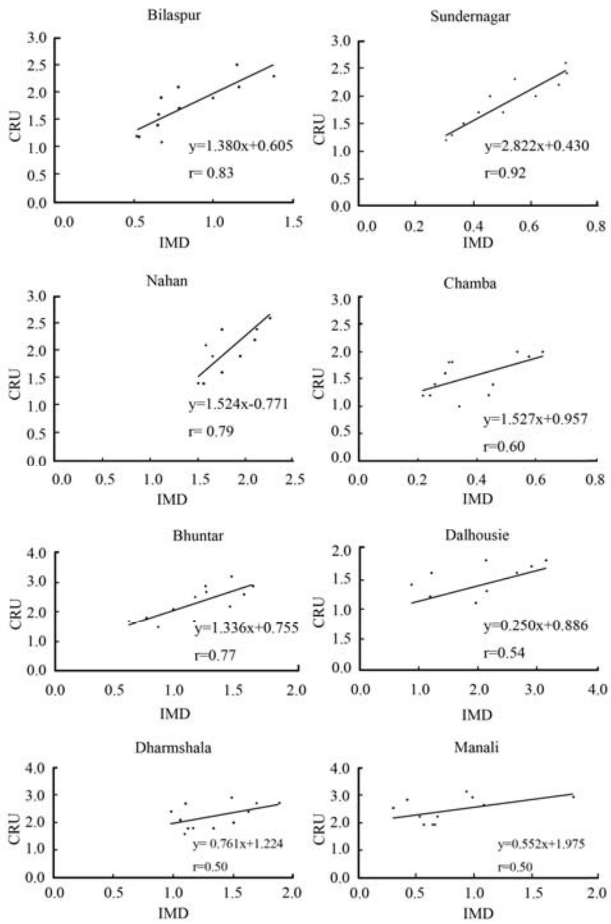

Figure 8 Correlation analysis for re-validation of CRU data within 10 km radius of IMD sites with surface data availability

method in a geospatial application. Figure 9 shows the seasonal as well as spatial variation of average wind speeds. Frequency of occurrences of regional wind speeds are represented by histograms. As observed in the annual CRU wind regime (Figure 6), the spatial variations of wind speeds in seasonal wind profiles (Figure 9) were explicitly influenced by elevation and resultant agro-climatic zones. Highest wind speeds in

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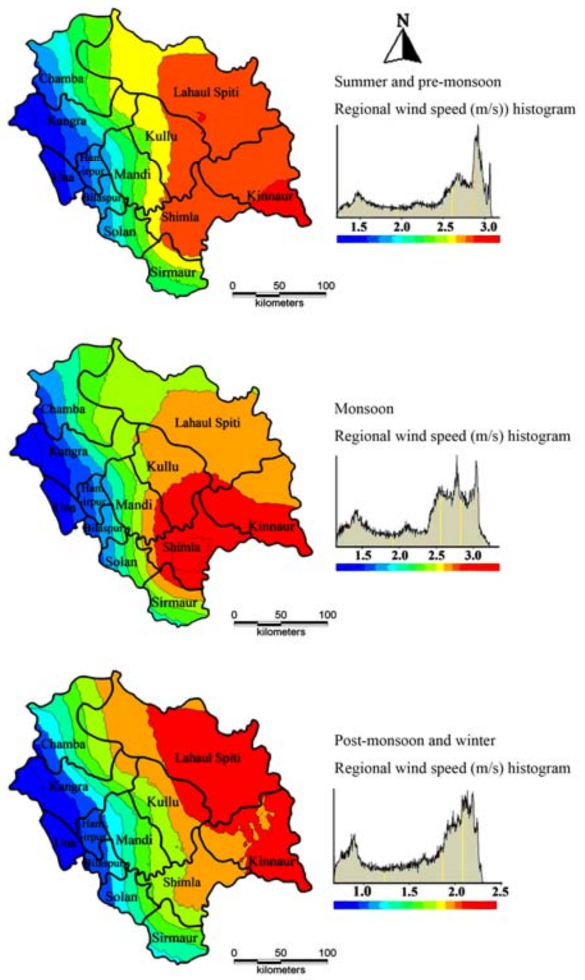

Figure 9 Seasonal wind profiles with spatial variations and frequency of occurrence of wind speeds for Himachal Pradesh

the range of 1~3.25 m/s were seen during Monsoon season (June to August) with high elevation zones of Lahual Spiti, Kinnaur, Kullu and Shimla districts showing above 2.5 m/s. Wind speeds declined during post-monsoon and winter seasons (October to February) and ranged as 0.75~2.25 m/s over the region, although high elevations zones showed above 2 m/s. During summer and pre-monsoon (March to May), wind speeds showed an increasing trend in the range of 1.25~3 m/s, high elevation zones having wind speeds appreciably above 2.5 m/s. Hence, the districts of Lahual Spiti, Kinnaur, Kullu and Shimla with annually consistent wind speeds above 2 m/s are suitable candidates for detailed wind exploration.

4.2.1 Validation of seasonal and regional variations in wind speed

Long term surface measurement based monthly average wind speeds at 10 IMD sites with data availability in Himachal Pradesh are shown in Figure 10. Monthly variations of surface wind measurements are consistent with the observations on seasonal wind profiles (Figure 9) based on CRU data. Most of the stations recorded peak wind speeds during the monsoon season. Winter months witnessed calm breeze awaiting a surge in the forthcoming summer.

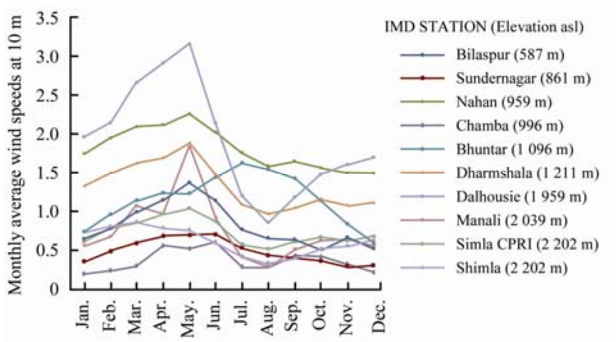

Figure 10 Monthly average wind speeds at IMD stations with data availability

Daily wind speeds in Himachal Pradesh were also studied. The daylight average wind speeds (8:30~17:30 hrs) were higher than the dark hours (17:30~8:30 hrs) for all the months recorded by IMD. These trends were observed in most of the sites although exceptions due to the micro climatic influences on wind speeds were noticed at certain stations.

The IMD sites were mostly located in low and middle elevation zones ranging from tropical to wet-temperate (< 3 500 m) which experience wind speeds below 2 m/s according to wind profiles based on CRU data. None of the available IMD sites represent high elevation zone where higher wind speeds (> 2 m/s) were investigated. Most of the IMD sites (except Shimla) measured wind speeds below 10 m, and hence the assumption of standardized measurements for data (mast height) sparse stations could be an underestimate according to power law in Equation 1. Hence, the actual wind speeds in many of the data sparse sites may be higher at 10 m. AWS wind speed measurements installed at 22 stations spread across Himachal Pradesh (shown in Figure 2) with better spatial coverage would aid in better validation of these results apart from removal of uncertainties such as data gaps, etc. Availability of more number of reliable wind measurement stations and detailed analysis of terrain features could facilitate micro-scale (1~10 km) wind resource assessment in Himachal Pradesh.

4.3 Small-scale wind applications in Himachal Pradesh

In order to explore the potential of wind technologies at an increased hub height, hourly surface wind speed measurements at IMD stations were estimated for 30 m using power law in Equation 1 and represented in Figure 11. More than 61% of measured hours in Nahan, 44% in Bhuntar and 18% in Dalhousie obtained wind speeds above 2 m/s. Over 29% of the measured hours crossed 4 m/s wind speeds in Bhuntar. These finding along with relatively higher wind speeds (> 2 m/s in high elevation zone) observed in seasonal wind profiles (based on synthesised CRU data) are indicative of the prospects of small-scale wind applications in Himachal Pradesh.

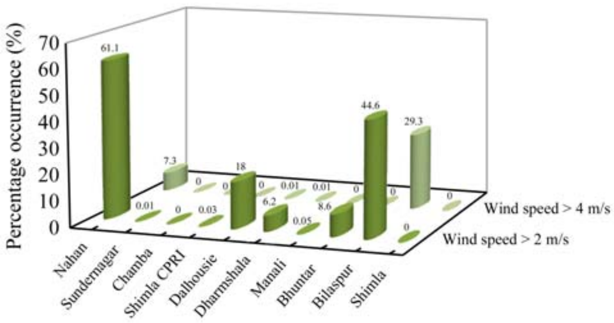

Figure 11 Percentage occurrence of winds above 2 m/s and 4 m/s from hourly measurements projected to 30 m hub height

With advancements in technology, small-scale wind turbines functional at moderately low wind speeds are technically feasible and economically viable (Cabello and Orza, 2010). Some of these are listed in Table 3. The Savonius rotor Vertical Axis Wind Turbine (VAWT) that can function in wind speeds as low as 1 m/s (Ayhan and Saglam, 2012) is of special interest in this region.

Wind pump for drawing water is an attractive small-scale wind technology for rural energy needs (Mathew et al., 2002). The agriculture intensive sub-tropical to wet-temperate zones of Himachal Pradesh could get benefited by wind pumps that function at low wind speeds. As seen in Nahan and Bhuntar, increased hub heights (30 m) could deliver prolonged winds above 2 m/s.

Table 3 Available small-scale wind turbines (European Wind Energy Association, 2012, http://www. wind-energy-the-facts.org/)

Rated power, P_{rated} (kW)	Rotor swept area (m^2)	Sub-category
$P_{rated} < 1$	A < 4.9	Pico wind
$1 < P_{rated} < 7$	A < 40	Micro wind
$7 < P_{rated} < 50$	A < 200	Mini wind
$50 k < P_{rated} < 100$	A < 300	(Not defined)

Wind based space heating systems have been assessed to be cost effective compared to many conventional fuel sources like fuelwood and electricity (Jaber et al., 2008). The colder alpine zone of Lahaul Spiti and Kinnaur where the wind speeds are relatively higher, could meet their space heating requirements through wind energy. Development of wind energy based water heaters is promising for such regions (Tudorache and Popescu, 2009).

Reduction in wind speeds and duration could be compensated by hybridizing wind with available alternative resources. Our assessment of solar energy potential in Himachal Pradesh substantiates that it receives monthly average global insolation (incoming solar radiation) > 4 $kWh/m^2/day$ except for the winter months (December and January). Higher altitude alpine zone (> 3500 m) receives lower insolation values but higher wind speeds. This trends inverts in lower altitude tropical zone i.e higher insolation and lower wind speeds (Ramachandra et al., 2011; Ramachandra et al., 2012). Hence wind-solar hybrid systems could be considered for endured energy supply in the region. Small-scale wind turbines could also be used in conjunction with diesel generators especially in remote areas (Clausen and Wood, 1999), although not a clean option. Battery charging based on wind systems supplements the energy requirements during reduced wind speeds.

4.4. Constraints

The present study provides a meso-scale

understanding of the wind regime in Himachal Pradesh. Wind technologies could be deployed in the region only after assessing the detailed wind characteristics, land availability and socioeconomic impact. This demands reliable and long term surface wind measurements at specific locations which are invariably influenced by the local terrain features. Wind characteristics like speed, power density, turbulence intensity and vertical profile variations influence the design of wind turbines for purposes like power generation, battery charging, water pumping or space heating. For example, turbulence intensity (ratio of standard deviation to average of wind speed) in Himachal Pradesh, based on IMD surface wind measurements exceeds 0.1 (Figure 12). These values are relatively higher (Bourgeois et al., 2012, http://www.meteotest.ch/fileadmin/user_upload/Windenergie/pdfs/Ext_abstract_dewek10_SaskiaBourgeois.pdf) and hence call for appropriate considerations in wind turbine design. Land availability for small-scale wind applications may not be a serious constraint. However, increased hub heights even for small turbines could be at the cost of the soil strength and land stability. Also, success of wind technology demands regular monitoring and sustained maintenance.

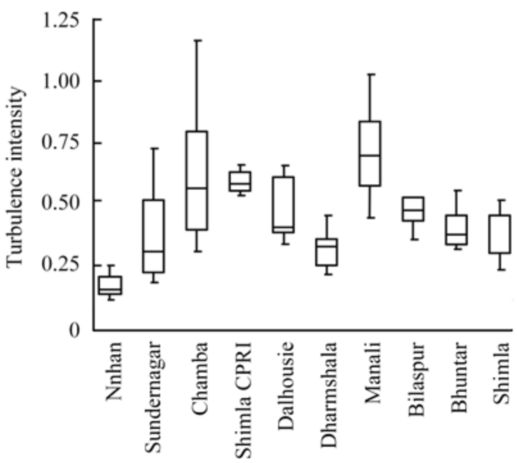

Figure 12 Turbulence intensity in Himachal Pradesh based on surface wind speed measurements

5 Conclusions

This study addresses the increasing need for regional wind energy resource assessment with focus on small-scale wind applications so as to meet the increasing energy demands in a decentralized manner, particularly in remote areas. Due to sparse and unreliable surface wind measurements available and expensive modeling alternatives, proven synthesized data were scrutinized for suitability in the study region of Himachal Pradesh. These data procured from NASA-SSE, NOAA-CIRES and CRU based on physiographical understanding of the complex Himalayan terrain were observed to have RMSE of 2.57 m/s, 1.92 m/s and 1.32 m/s on validation with long term surface measurements. Annual wind regimes mapped from all these data using geospatial techniques consistently highlighted the dependence of wind speeds on elevation gradient and resultant agroclimatic zones. Wind data from CRU, selected as the most representative values were re-validated by correlation with surface measurements in proximity. Seasonal wind profiles mapped using CRU data were compared with wind variations in surface measurements. Wind speeds in the range of 1-3.25 m/s were seen during Monsoon season (June to August), 0.75-2.25 m/s during post-monsoon and winter seasons (October to February) and 1.25-3 m/s during summer and pre-monsoon (March to May). High elevation zone including Lahual Spiti, Kinnaur, Kullu and Shimla districts showed wind speeds above 2 m/s for all seasons and were identified as suitable candidates for further wind exploration. Certain small-scale wind applications like low wind speed Savonius rotor Vertical Axis Wind Turbine (VAWT), agricultural water pumps, wind-solar hybrids, space/water heaters, battery chargers etc. suitable for the study region have been discussed, while also mooting the possible constraints of dissemination. Employment generation through appropriate mechanisms mobilizes local people in these efforts. More importantly, resolute organizational support will ensure smoother penetration of wind technologies. Meeting the energy demands through clean resources like wind envisions a sustainable future for Himachal Pradesh as well as other regions neglected in the conventional wind assessment studies.

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