INTRODUCTION
The international energy outlook 2004 project shows a strong growth in worldwide energy demand over the twenty-four year projection from 2001 to 2025. The total world consumption of marketed energy is expected to expand by 54% from 404 quadrillion British thermal units (Btu) in 2001 to 623 quadrillion Btu in 2025. The developing nations of the world are largely expected to account for the increment in world energy consumption. In particular, energy demand in the emerging economies of developing Asia, which include China and India, is projected to be more than double over the next quarter century (IEO, 2004).

With the fossil fuel prices projected to remain relatively low, the cost of generating energy from other fuels is not expected to become competitive. As a result, much of the increment in future energy demand in the reference case is projected to be supplied by oil, natural gas and coal. However, the environmental programmes or government policies, particularly those designed to limit or reduce greenhouse gas emissions i.e., Kyoto protocols are implemented. The outlook could change and non-fossil fuels including nuclear power and renewable energy sources, such as hydroelectricity, geothermal, biomass, solar and wind power could become attractive and important (WEC, 2005).

1.1 Energy scenario in India

India ranks sixth in the world in total energy consumption and needs to accelerate the development of the sector to meet its growth aspirations (Raghuraman, 2002). The energy consumption was increased from 4.16 quadrillion in 1982 to 12.8 quadrillion in 2001 and is due to the increasing population, rapid urbanization and industrial growth.
Higher energy consuming sectors are industry and transportation. Energy shortages act as a major barrier which could obstruct the stream of development. About 25% of the primary energy sources such as crude oil and natural gas are needed for developing countries like India. Therefore it is very essential to import this from other countries. The rise in imported oil has been the focus of serious concerns due to the pressure placed on scarce foreign exchange resources which is largely responsible for energy supply shortages. The sub-optimal consumption of commercial energy adversely affects the productive sectors, which in turn hampers the economic growth. Replacing coal and other fossil fuel-generated electricity, supplied to India’s cities with energy from renewable energy sources could aid in reducing air pollution and help to meet the growing energy needs of the country’s large metropolises as well. Figure 1 shows India’s fuel share of energy consumption (Btu), 2001.

![India's Fuel share of Energy Consumption, 2001 (Btu)](image)

**Figure 1.** India’s fuel share of energy consumption (Btu), 2001
1.2 Renewable energy scenario in India

Being a tropical country, India is abundantly endowed with renewable energy sources. Recognizing the importance of tapping renewable energy sources for power generation, India has been working in this direction for more than two decades. The exploited potential of renewable energy is as follows:

<table>
<thead>
<tr>
<th>Source/Technologies</th>
<th>Approximate potential</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power from renewables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind (MW)</td>
<td>45,000</td>
<td>2,100</td>
</tr>
<tr>
<td>Small hydro (up to 25 MW)</td>
<td>15,000</td>
<td>1,663</td>
</tr>
<tr>
<td>Biomass / Baggage based co-generation (MW)</td>
<td>19,500</td>
<td>343</td>
</tr>
<tr>
<td>Solar PV power MW/Km²</td>
<td>20</td>
<td>47</td>
</tr>
<tr>
<td><strong>Energy recovered from wastes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban and Industrial waste (MW)</td>
<td>17,000</td>
<td>15.15</td>
</tr>
<tr>
<td><strong>Energy for rural areas</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biogas Plants (Millions)</td>
<td>12</td>
<td>3.128</td>
</tr>
<tr>
<td>Improved Chulha (Millions)</td>
<td>120</td>
<td>32.89</td>
</tr>
</tbody>
</table>

(Source: Ministry of Non-conventional Energy Sources (MNES) & Planning Commission, 2004)

Among the renewable energy sources, wind energy has an edge because of its technological maturity, good infrastructure and relative cost competitions. In addition to these direct benefits, the wind power projects also resulted in substantial socio-economic and environmental benefits. The estimated environmental benefits of installing wind farms would be resulted in reduction of the following emissions annually:

- **CO₂**: 2100 metric tonnes / MW
- **SO₂**: 2.5 metric tonnes / MW
- **NOₓ**: 1.7 metric tonnes / MW
- Total suspended particulate: 0.5 metric tonnes / MW
The socio-economic sector of wind power has resulted in direct and indirect generation of employment. It has been estimated that for each Mega Watt (MW) of installed capacity of wind farms, there is an employment potential of three skilled operators and two unskilled persons. The indirect employment opportunities are about four times of that direct employment (i.e., 20 man power). During the construction phase, lasting about six months, additional employment is available to fifty local people for civil and electrical works (IREDA, 2001).

The scenario of wind power generation in India started looking up in 1999 and this upswing is still continuing. The main factors that contributed to this positive growth are

- Technological maturity and introduction of machines suitable for Indian conditions has resulted in overall higher capacity utilization. This factor has helped in attracting more investment from the private sector.
- Introduction of bigger capacity and more cost-effective wind turbines.
- Better site selection due to more sophisticated and rigorous wind resource assessment and micro siting.

1.3. History of wind power and development

The wind power has been utilized for many centuries. The first windmill was used mainly for grinding and pumping water in Persia during 500-900 AD. By 1800 AD, about 20,000 modern windmills were in operation in France alone and in Netherlands, about 90% of the power used in industry was based on wind energy (Ackermann and Soeder, 2002). The pioneering Dane Poul LaCour built the first wind energy turbine that generated electricity. The large-scale development of wind energy began after the oil crises during 1970s, with wind farms being installed in California under an attractive tax
scheme. In the beginning of the 1990s, the USA was leading in installed wind energy capacity. Germany took over around the mid-1990s due to effective government intervention. At the start of 2003, the world-installed capacity of wind energy was 31.162 GW in 1991 (Windicator). The main countries involved were Germany, USA, Spain, Denmark and India. In the last five years, the capacity increased annually by about 30%. The largest annual increase at country level (48%), in the period 1991-2001, was in Germany (European Commission, 1999; Morthorst, 1998).

The rapid growth in wind capacity is reflected in the development of wind turbine technology. A significant trend is up scaling of the size of the turbines, increasing their output, reducing the generation costs and the visual impact on the landscape (Beurksens, 1999). The average size of installed commercial turbines has increased from about 30 KW with rotor diameter of 10 m in the mid-1970s to 1 MW at present (rotor diameter 80 m). The largest commercial wind turbines are also now available with 2 MW capacity. Other developments over the last few decades have better control on power regulation systems and focus on direct drive turbines. The latter involves higher investment costs (Bundesverband WindEnergie, 1995-2000, 2001), but the direct drive turbine cost may be lower because no gearbox is needed. Furthermore, the energy conversion efficiency is improved (BTM, 2001; European Commission, 1999).

As illustrated, there is recently a large policy interest in wind energy based on various arguments. First, wind energy reduces dependency on and payments for imported fuels. Second, it diversifies energy carriers for the production of electricity. Furthermore, it can increase the flexibility of the electricity system as demand changes and it saves fossil fuels for other applications and further generations. Finally, wind electricity
reduces pollution and emissions, such as NOx and CO$_2$, that are produced by conventional energy systems (Turkenburg, 2000). As wind energy becomes more and more competitive, many authors expect that a strong growth of installed wind turbines continues for a number of decades (BTM, 2001; IPCC, 2000; Johansson et al., 1993; Lazarus, 1993; Shell, 1995; World Energy Council, 1994; EWEA and Greenpeace, 2002; Turkenburg, 2000).

Hanagasioglu (1999) reviewed the historical background of wind energy systems and he stated that wind and wind energy have always played an important role in the historical and economical development of Asia including Anatolia. Bellaaramine and Urquhart (1996) investigated wind energy in the 1990s and beyond. They stated that wind energy is being considered as a viable alternative energy source with the objective of reducing harmful effects of conventional electric power generation. The contribution of wind energy utilities has increased considerably during the past decade.

1.4. Wind energy scenario

1.4.1 Wind energy in the world

The reassessed gross wind power potential of the country stands at 45,000 MW, but the technical potential is about 30% of the total gross potential, which accounts to about 13,000 MW. The total installed capacity by the end of 2003 is 2110 MW (AWEA & EWEA). The increased capacity of wind power generation has put our country in a recognized place in the development and utilization of renewable energy especially in the wind power sector. Cumulative global wind energy generating capacity reached to 39,294 MW at the end of the year 2003. Figure 2 shows the top five wind energy markets in the world.
1.4.2 Wind energy in India

Renewable energy like wind energy is indigenous and can help reducing dependency on fossil fuels. This also provides national energy security at a time when decreasing global reserves of fossil fuels threatens the long term sustainability of the Indian economy. With abundance of wind energy resources in many parts of the country, especially along the long coastline, electricity generation through wind energy provides a viable and environmentally friendly option. The wind resources assessment program is carried out in India to reassess the wind power potential covering around 900 wind monitoring and mapping stations. So far, 208 wind power potential sites have been identified in thirteen states which include Tamil Nadu, Gujarat, Andhra Pradesh, Karnataka, Kerala, Madhya Pradesh and Maharashtra. The state-wise installed capacity of wind power in India is presented in Map 1 and Figure 3.
Map 1. State wise installed capacity of wind power in India as on end of March 2004
Among the identified states, Tamil Nadu has the highest wind power installation capacity of 990.3 MW and 1361.6 MW during 2003 and 2004 respectively (www.windpowerindia.com). There has been a steady increase in the private sector projects taken up during 2004 when compared to the previous year. In spite of the development in the wind energy sector in India, the growth is still lagging behind the developed countries like Europe and USA and is due to the lack of advanced technology and policies (Mangotra, 2001). As far as the Indian Government is concerned, the technology related priority areas, where further developmental work is required are as follows:

- MW size wind power systems
- Wind machines for low wind regimes
- Improved rotor blades

Figure 3. State wise installed capacity of power in India
• Advanced control systems
• Development of cheaper materials
• Integration of wind with weak grids
• Power quality improvements

On the policy front, India should follow European countries to increase the wind power potential. Great strides in computers and development of wind power mapping tools and methods have now made it possible to update and refine the wind resources in India. These new techniques have the potential to place vastly more information in the hands of public, enabling any one from major developers to individual enthusiasts to identify prospecting the sites for wind energy systems. Of course, mapping is just the first stage of the siting process. Promising sites identified in maps must be confirmed through field assessments and monitoring, and other hurdles such as permitting environmental impact assessment must be overcome. Nevertheless, the availability of more detailed wind resource information should accelerate the siting process and enable more people and companies to participate in it.

1.5 Wind energy resource assessment models

Wind energy is more variable and diffuses energy flux than other renewable energy resources. To assess the economic viability, it is fundamental to describe the variation of wind velocity spatially and temporally, which will allow us to estimate the future power output. This analysis (wind distribution pattern) provides an opportunity to optimize the wind energy conversion technology which ultimately resulted in low cost per kilowatt per hour (Wind power, 2002; Ulgen and Hepbasli, 2002).

Analysing the wind energy potential requires statistical assessment of the wind characteristics, and more particularly the long term average of the wind speed and its
frequency distribution. To fulfill this, it is necessary to use mathematical functions that accurately fit the wind speed frequency and duration curves. These mathematical functions can, later on, help in predicting the output of wind mills.

Justus et al. (1976) applied the Weibull and Log-normal distribution to wind speed data, for more than hundred stations in the USA and concluded that the Weibull distribution rendered the best fit. To describe the available wind distribution at a site and analyze the energy exchange between the wind and wind energy conversion systems (WECS), the Weibull and Rayleigh distribution are commonly used.

Amongst the most common distribution models, the Weibull function is accepted as the best model. Research evidences showed that the Weibull density function has its own merits such as great flexibility and simplicity. It also allows satisfactory estimates of the skewness of wind speed distribution (Hennessey, 1977; Lun and Lam, 2000; Ulgen and Hepbasli, 2002; Dorvlo, 2002).

There are several methods to calculate the Weibull distribution, such as the maximum likelihood method, the proposed modified maximum likelihood method and the graphical method (Lun and Lam, 2000; Seguro and Lambert, 2000). The Weibull parameters c and k of the Weibull distribution function have been explored extensively for many locations (Lalas et al., 1983; Nfaoui et al., 1998; Feretic et al., 1999).

In this respect, much attention has been given to the Weibull function which is a special case of generalized gamma distribution (Lysen, 1983; Johnson 1985; Hennessey, 1977; Katsoulis and Metaxas, 1992). Rehman et al. (1994) estimated the Weibull parameters for ten anemometer locations in Saudi Arabia and found that the wind speed distribution was well explained by Weibull distribution function.
Similarly, many authors have examined wind energy potential in one or more selected locations in Jordan using Weibull distribution model (Qashou et al., 1986; Habali et al., 1987; Anani et al., 1988; Habali et al., 1988; El-Hayek and Anani, 1989; Shabbaneh and Hasan, 1997; Mayhoub and Azzam, 1997).

The variation of wind velocity is often described using the Weibull two parameter density function. At present, this statistical method is widely accepted for evaluating local wind load probabilities and can be seen as a standard approach (Musgrove, 1988; Persaud et al., 1999; Seguro and Lambert, 2000; Lu et al., 2002).

Mani and Mooley (1983) have estimated the wind speed using Weibull distribution for both monthly and annual wind speed data sets, of individual stations. Similarly, Gupta (1986) estimated the Weibull parameters for annual and monthly wind speed distributions for five locations in India and observed that numerical values of Weibull parameters will help in estimating the monthly and annual output of power of any wind machine.

The wind energy potential in Turkey has been analyzed by Kulunk (1993) using Weibull distribution. The author used wind speed data of four locations and showed that the site with yearly mean wind power densities of 73.76 was most suitable for harnessing the wind power. The variability of the wind power on the western coast of Anatolia was analyzed using Weibull distribution for estimating the wind speed and wind power (Incecik and Erdogmus, 1995).

The proper and beneficial development of wind power at any location, wind data analysis and accurate wind energy potential assessment are the main key requirements. Ettoumi et al. (2003) used statistical bivariate modeling to study the statistical features of
wind speed at Onam in Algeria. The study concluded that Weibull probability
distribution function was also found to fit the monthly frequency distribution of wind
speed measurements.

The estimation of the annual Weibull parameters from twenty locations in
Navarre was done using the hourly mean wind speed data and found best fit (Garcia et
al., 1998). Ansari et al. (1986) also used hourly wind speed data and developed a wind
atlas in 1986 and this atlas provides information on contours of wind speed, monthly
values and prevailing wind direction.

Recently, Li (2000) and Lu et al. (2002) conducted mathematical investigations
using the two parameter Weibull wind speed distribution to examine the wind power
potential and wind turbine characteristics in Hong Kong.

The wind characteristics of eleven sites in the windy regions of Morocco have
been analyzed. On an annual scale, the observations of the distribution of hourly wind
speed are better fitted by the Weibull hybrid distribution in contrast to the Weibull
distribution (Nfaoui et al., 1998). The Weibull hybrid distribution which is a revised
version of the Weibull function shows more accuracy to fit the observed data (Knidiri and
Laaouina, 1986; Nfaoui et al., 1994). Methods for estimating the Weibull hybrid
distribution parameters from a given data are being studied, and are described elsewhere
(Lysen, 1983; Johnson, 1985; Nfaoui et al., 1994).

Several studies have stressed the importance of considering seasonal variation in
the wind velocities when estimating wind regimes using Weibull distribution (Ulgen
and Hepbasli, 2002; Kainkwa, 2000; Lu et al., 2002; Mathew et al., 2002; Sulaiman et
al., 2002).
Hammouche (1990) published “the wind atlas of Algeria” giving the results of the statistical study of 37 stations using the Weibull distribution. These results were used to establish the first wind map of Kasbadji-Merxouk (1994). This map was improved by the same author in 1999, by increasing the number of stations to 46 and using the hybrid Weibull distribution (Kasbadji-Merxouk, 1999).

Jagamshetti (1999) addressed a statistical model and monogram method to investigate wind turbine characteristics for various wind turbine generators by using the same sets of wind data at Kappadgudda wind power station, India.

1.6 Wind Resources mapping using Geographical Information System (GIS)

Geographical Information System is a valuable tool for wind resources assessment and development because it utilizes the significant spatial and temporal components found in both. The wind energy potential is generally and strongly influenced by (i) location (ii) topographic features (iii) surface roughness and (iv) sheltering. GIS techniques not only identify sites but also provide wind potential maps and other useful base information such as inland areas, rivers, oceans, coastal areas and lakes.

Dao et al. (1998) presented wind data analysis for two sites, and they are Trombay and Mumbai in India, to assess their wind power potential. The study revealed that a low or medium power windmill could be operated at the site, with an annual availability factor of about 76% and 57% respectively.

Hillring and Krieg (1998) have calculated wind energy using a modeling tool such as WASP, which is a program for extrapolating wind data in horizontal and vertical direction using ground surface data on topography and land use.
The regional wind energy potential of Turkey was investigated by Oztopal et al. (2000). The wind speed and wind energy of Turkey have been mapped and its potential areas identified. Using information from a questionnaire and available published literature, Geographical Information System (GIS) assisted wind farm location criteria was developed by Baban and Tim Parry (2001) for UK. A GIS software (IDRISI) was employed to apply these criteria using two different methods to combine information layers for a site in Lancashire.

Jayakumar et al. (2002) have estimated wind power potential in eighteen stations of Tamil Nadu using Gamma distribution and the wind power potential areas were mapped using ArcView 3.2a. Krewitt and Nitsch (2003) also developed a GIS based approach to analyze the effects of different nature conservation criteria on the wind energy potential in quantitative terms.

Khan et al. (2004) have generated a wind energy map of Bangladesh, which incorporates several micro scale features, such as terrain roughness, elevation, etc., with a mesoscale model. Several mesomaps were obtained from global databases, and a suitable model was chosen and modified for a 30-meter elevation.

The wind energy potential and feasibility of some locations for East Mediterranean region of Turkey was analysed by Bilgili et al. (2004). The wind speed mean values, wind directions, wind potential and the frequency distributions were determined and finally, they produced the wind atlas of these regions in the form of contours of constant wind speed and wind potential.

Energy plays a pivotal role in the sustenance of modern economy. Further economic growth crucially depends on the long term availability of energy in increasing
quantities from sources that are affordable, accessible and environmentally-friendly renewable energy like wind power. Thus, the present study focusses on the availability of wind energy resources in Tamil Nadu using GIS for wind resources mapping to analyse temporal changes, which in turn help wind farm developers and policy makers to appreciate and adopt environmentally clean energy sources.

The objectives of the present study are:

❖ To assess the wind energy potential in different parts of Tamil Nadu using Weibull and Gamma distribution models
❖ To prepare GIS based spatial maps and analyse the wind potential according to the climatological seasons
❖ To study the harmonic features of wind speed records at randomly distributed stations scattered over Tamil Nadu
❖ To prepare ground data extrapolation wind speed maps at standard height of 30 m and 50 m and
❖ To prepare topographical maps of Tamil Nadu.