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*Research Article*

# Wind Energy Development in India and a Methodology for Evaluating Performance of Wind Farm Clusters

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With maturity of advanced technologies and urgent requirement for maintaining a healthy environment with reasonable price, India is moving towards a trend of generating electricity from renewable resources. Wind energy production, with its relatively safer and positive environmental characteristics, has evolved from a marginal activity into a multibillion dollar industry today. Wind energy power plants, also known as wind farms, comprise multiple wind turbines. Though there are several wind-mill clusters producing energy in different geographical locations across the world, evaluating their performance is a complex task and is an important focus for stakeholders. In this work an attempt is made to estimate the performance of wind clusters employing a multicriteria approach. Multiple factors that affect wind farm operations are analyzed by taking experts opinions, and a performance ranking of the wind farms is generated. The weights of the selection criteria are determined by pairwise comparison matrices of the Analytic Hierarchy Process (AHP). The proposed methodology evaluates wind farm performance based on technical, economic, environmental, and sociological indicators. Both qualitative and quantitative parameters were considered. Empirical data were collected through questionnaire from the selected wind farms of Belagavi district in the Indian State of Karnataka. This proposed methodology is a useful tool for cluster analysis.

## 1. Introduction

On account of continuous industrial development clubbed with depletion of fossil fuels and emerging environmental consciousness, the demands for alternative energy resources have been increasing exponentially in the 21st century. With growing demand for energy, increased environmental pollution, and depleting energy sources, human society today faces multiple challenges of transition towards a sustainable development and the poverty eradication. In dealing with sustainable development energy is one of the main factors that must be considered [1]. The concept of sustainable development according to Brundtland report [2] is based on the idea of meeting the needs of the present without compromising the ability of future generations to meet their own needs. In developing economies clean and energy-efficient technologies can contribute to sustainable development and energy security [3].

Energy planning involves finding a set of sources to meet the energy requirements in an optimal manner. As an alternative means and of meeting global energy demands, renewable energy sources, including solar, wind, mini-hydropower, geothermal, and biomass energy, are receiving increasing attention. Being an affordable and clean energy source, wind energy is among the world's fastest growing renewable energy forms [4]. The challenge for India today is rapid adoption of renewable energy sources to power growing economy at a price that consumers can afford and on a scale large enough to make a major dent in shortages. India has added large-scale conventional power resources, as demand for power has grown since decades [5]. Today there are alternate options available in the form of solar and wind power technologies and renewable energy (RE) resources have become commercially available in the marketplace. This has added additional options for policymakers who are concerned with the technical, economic, and environmental characteristics

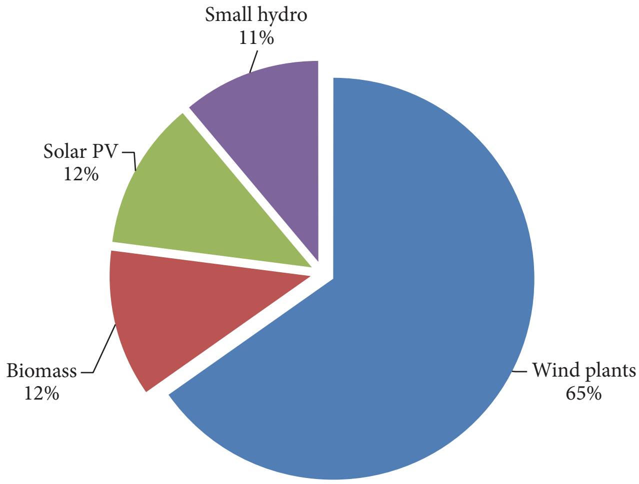


Figure 1: Grid interactive power generation.

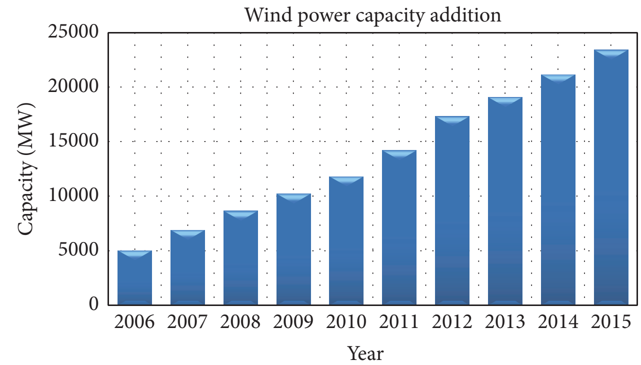


Figure 2: Cumulative and annual wind capacity additions, India.

of a future power system that keeps pace with economic growth.

## 2. Renewable Energy in Power Sector

India with over 1.27 billion population is the seventh largest geography and today ranks fourth among high energy consuming countries in the world. In the past three decades total primary energy consumption has increased manifold from 18 MTOE (in 1980) to 104 MTOE (2011) in India [6]. Also, with the growing economy, the dependence of energy has increased magnanimously due to growing industrialization and the impetus given to infrastructure development. India is importing 79% of the petroleum it needs and has been heavily relying on imported coal. Therefore it is necessary now that India looks for domestic sources of energy [7]. India's renewable energy potential is very vast and most of it remains untapped. According to recent estimates solar potential is greater than 10,000 GW for India and wind potential could be higher than 2,000 GW [8, 9]. The percentage distribution of grid interactive RE power generation [9] is presented in Figure 1.

To completely utilize the large energy potential, India requires new initiatives from both state and union governments. These new initiatives should be beyond existing policies and programs [5]. Renewable energy contributes about 13% of the total power generation in India [8] and this contribution is slowly increasing. Grid interactive power generating plants from RE sources constitute 38821 MW with the major share of wind energy plants (25088 MW) followed by biomass/bagasse cogeneration plants (4688 MW), solar photovoltaic (4879 MW), and small hydro (4177 MW). Municipal solid wastes accounts for a very small fraction in power generation [MNRE]. India's overall energy potential is more than the current total energy consumption [9]. India's renewable energy programme is the biggest and most extensive. The Government of India is committed to provide a conducive environment for harnessing offshore wind energy in India. The Government envisions carrying forward the development of offshore wind energy in the country, to overcome the existing barriers and to create technological and implementation capabilities within the country [8]. The broad vision behind the integrated energy policy is to meet the demand for energy services of all sectors [10]. The Ministry of New & Renewable Energy (MNRE), Government of India, has set a target of achieving overall renewable energy installed capacity of 41,400 MW by 2017.

*2.1. Growth of Wind Energy.* Wind energy is a very important contributor in the global power sector today, contributing nearly 4% of overall electricity generation. This achievement is the result of exponential growth in wind power development across the world, particularly in the last decade. Continued technological development and innovation in design and manufacturing has resulted in large-scale deployment of onshore and offshore projects [11]. Today's modern wind turbines with latest technology have made the wind energy generation into a mainstream electricity generation option. The primary drivers for this development include energy security, climate change, and energy access, while employment and economic development are additional benefits [12, 13].

In India, preliminary assessments along the coastline have indicated prospects of development of offshore wind power. With nearly 24 GW of wind power capacity India ranks 5th in the world. India also has an ambitious plan of increasing wind energy share in the 12th five-year plan. This requires considerable investments in the core sectors including energy [14]. Capacity addition in 2015-16 is expected to be around 4,000 MW. Today, there are nearly 20 plus wind turbine manufacturers in India, with about 52 turbine models certified by the National Institute of Wind Energy (NIWE) which is the nodal agency for wind development for grid connection [15]. Over the years the growth in wind power development has been exponential and is shown in Figure 2 [16].

In March 2015, renewable energy (RE) sources formed more than 12% of India's total installed capacity. Between 2006 and 2015, the wind industry added between 1500 and 3000 MW per annum. The primary reason for this is that for more than a decade now wind technology has been technically and commercially viable in India. Today, wind energy is a key constituent of India's energy basket. Recognizing the immense potential of wind resource, the Indian Government has set a target of installing 60 GW of wind by 2022. This implies a quantum jump from the current level of annual deployment. Therefore, the Prime Minister's Council on Climate Change has proposed to induct a National Wind Energy Mission under India's National Action Plan on Climate Change (NAPCC) [9, 13].

Even though there is a huge potential for wind energy, there are also many issues to be addressed for exploiting the full potential. Particularly, most regions of India are classified as low wind energy regimes necessitating identification of appropriate models for estimation and realization of potential. Besides, proper site selection, new composite materials for wind turbines, new techniques of manufacturing wind turbines and attractive policy for wind energy, and so forth are the other aspects to be focused on. At present, there are hardly any measures for estimating the performance of the existing wind-mill clusters. In the present research an attempt has been made to address this issue by proposing a quantitative and comprehensive performance index for the analysis of wind-mill clusters.

In India the southern state of Tamil Nadu leads in wind energy extraction followed by Maharashtra, Gujarat, and Karnataka. The coastal region (west coast) of the country experiences high wind speed which ranges from 3 to 5 m/s annually. The southern and central part (west coast) experiences higher wind speed during monsoon (June–Sept) which will be more than 5 m/s. Estimation shows that the western coast of Karnataka, Tamil Nadu, Kerala, Maharashtra, and Gujarat and plains of Rajasthan, Gujarat, and Karnataka are the ideal places for wind energy harvesting where the annual average wind speed is higher [17].

## 3. Wind Farm/Cluster Definition

Wind farms comprise number of wind turbines. These turbines are built on areas that are conductive to consistent good winds. In a "wind farm" a group of wind turbines are built in close proximity to each other to form a cluster. More turbines can be added based on the electricity demand. Basically these wind turbines convert the kinetic energy available in wind into mechanical energy and then to electricity through a generator. A modern wind turbine comprises three integral components. The rotor which is the main component includes the blades for converting wind energy to an intermediate low speed rotational energy. The generator component includes the electrical generator, the control electronics, and a gearbox for converting the low speed rotational energy to electricity. Finally the structural support component includes the tower which orientates the rotor to the wind energy source. Majority of the wind turbines installed for power generation are horizontal axis turbines as these can adjust their blades to avoid high wind storms and can collect maximum amount of wind energy. The vertical axis wind turbines are rarely used [18]. The energy generated from these wind farms is supplied to customers through a central grid. In a large wind farm the space between the wind turbines is used for agricultural purposes. Each turbine in a wind farm is connected with another through a communication network and a voltage system. In many instances to take advantages of strong winds over an ocean or sea, wind turbines may be located offshore as well. To select ideal locations for setting up of wind farms, wind power density (WPD) is expressed in terms of the elevation above ground level over a period of time, taking into account velocity and mass [19].

*3.1. Review of Wind Farm Cluster Performance.* Today wind turbine generators (WTGs) are almost comparable to conventional units of power generation in terms of both cost and capacity ratings due to the development in wind technology [20]. The performance of a WTG is affected by reliability, power factor, technical availability, and capacity factor [21]. Doubling the wind speed magnifies the power developed by 9 times, as power is proportional to cube of velocity. Also wind velocity variation has an impact on the economics and smooth running of the wind energy conversion system. Today variable speed generations are available in markets which are cost effective [22]. Power density and annual mean wind speed need to be measured in order to assess the long term trend of wind speed [23]. The annual energy output at a location also depends on interconnection with electric networks, height of installation, effect of wind gusting, and so forth [24]. According to expert's prediction, by the yr 2020 wind power can capture 5% of the world energy market with improved technologies and superior economics [25].

There are many notable studies on development and performance of wind farms in literature. Lee et al. [25] constructed a comprehensive evaluation model to select a suitable location for developing a wind farm in Taiwan. Şenel et al. [26] performed a study to determine the current position of wind energy in Turkey and policies to increase the usage of wind energy. Sholapurkar and Mahajan [10] carried a review on Maharashtra's (India) wind energy progress, considering factors such as wind project installations, total capacity, declared wind sites, and wind power density at different altitudes. Barin et al. [27] developed a multicriteria decision analysis (MCDA) to evaluate the operation of the renewable energy sources-wind generators, microturbines, photovoltaic cells, and fuel cells. Himri et al. [28] worked on wind farm development in Algeria. Wind speed data over a period of almost 10 years was utilized, in order to assess the energy output of a wind farm in terms of gross energy, renewable energy delivered, specific yield, and wind farm capacity factor. Phadke et al. [29] assess the technoeconomic onshore wind potential in India at three hub heights: 80 m, 100 m, and 120 m. Nemes and Munteanu [30] developed a probabilistic model for capacity factor and technical efficiency estimation in the wind farms of North-East of Romania. A technoeconomic evaluation of small wind electric generator (SWEG) projects for providing decentralized power supply in remote locations in India is presented by Nouni et al. [31] Also Rajakumar and Nagesha [32] estimated the performance of a wind-mill cluster adopting a multicriteria approach. The methodology was implemented by collecting empirical data from three wind-mill clusters located at Chitradurga, Davangere, and Gadag in the southern Indian State of Karnataka.

To improve the reliability of the system and to rectify the failures it is important to analyze the performance of a wind farm. The WPD which is a prime parameter varies with different locations as well as with seasons in India. From April to September high WPD is observed and during October to December low WPD is observed. The energy generation at a site varies due to speed of the wind speed and other technical factors. The power curve is the most important performance criterion. On the basis of the power curve the annual energy output can be calculated for a given site which indirectly gives the Capacity Utilization Factor (CUF) of a wind farm. Other factors which describe the performance of a wind farm are site factor, transmission losses, net energy output, individual WTG performance in the cluster, and so forth. Further, parameters like return on investment or cost/unit, machine availability, and grid connectivity are also relevant in estimating performance of any wind farm [32]. A lot of quantitative and qualitative factors are involved in decision making process. Energy evaluations may involve both quantitative and qualitative factors. These should cover technical, economic, environmental, and socioeconomic factors [33]. In the earlier studies multiple evaluation criteria were used which include (a) technical (efficiency, primary energy ratio, safety, reliability, and maturity); (b) economic (investment cost, operation and maintenance cost, fuel cost, net present value, payback period, service life, equivalent annual cost, etc.); (c) environmental ($CO_2$ emission, $NO_x$ emission, $SO_2$ emission, particles emission, land use, noise, etc.); and (d) social (social acceptability, job creation, social benefits, etc.) parameters [34].

*3.2. Details of the Wind Farm under Study.* Karnataka is one of the top five states in India having high potential of wind energy generation [35]. It has about 30,000 MW of officially estimated renewable energy (RE) potential, making it one of the country's top five RE-rich states. Out of 15.0 GW installed electricity generating capacity in Karnataka, RE sources contribute for about 5.1 GW or 30% [36]. By March 2016, the total allotted wind energy generation capacity to various groups was 13983 MW. But the commissioned capacity stands at 2916 MW (20.84%) only, which is 20% of allotted capacity. 3427 MW of allotted capacity was cancelled due to several reasons.

The district of Belagavi is located in north western part of the state of Karnataka. It has an average elevation of 751 m. The Belagavi district wind farm cluster consists of 318 wind turbine generators with a total installed capacity of 319.3 MW. The installed capacities of wind energy ranged from 250 kW to 2 MW and cost per MW varies for different developers. In Belgaum district wind cluster, the wind farms are located in many places, namely, Chikkodi, Ramdurg, Raibag, Saundatti, Hukkeri, and Belagavi. The wind potential variability lies in the range of 4.27 to 6.75 m/s annual wind velocity with wind power density (WPD) ranging from 170 W/m$^2$ to 350 W/m$^2$ at 50 m hub height. The total installed capacity is 319.3 MW as on July 2015 with 318 total WTGs [36]. The district of Belagavi is one among the top five districts having higher potential for wind energy generation. For the analysis a questionnaire-based research survey was conducted. Opinions and judgments were collected from wide variety of experts and stakeholders. All respondents were knowledgeable about the power sector and were familiar with clean, efficient, and renewable energy generation technologies and the barriers hindering their widespread diffusion and adoption. The details of wind turbine installations are presented in Table 1 [36].

Table 1: Details of Belagavi district wind turbine installations.

| Wind farm | Nor. of WTGs | Installed capacity in MW |
|---|---|---|
| Chikkodi | 84 | 94.85 |
| Hukkeri | 05 | 02 |
| Raibag | 38 | 59.55 |
| Ramdurg | 25 | 20 |
| Saundatti | 95 | 82.5 |
| Belagavi | 71 | 60.4 |
| Total | 318 | 319.3 |

*3.3. AHP Methodology for Wind Cluster Performance Analysis.* One of the main objectives of this work is to develop a methodology to evaluate the performance of wind farm clusters. For this purpose the Analytic Hierarchy Method (AHP) has been employed. In AHP methodology [37] initially problem is defined with the main objective. In the next step, the criteria are identified and the problem is structured in a hierarchy. Then each element is compared on a 1–9 scale (ranging from equal importance to extreme importance) and finally calculations are done to find the max. eigenvalue, consistency index (CI), consistency ratio (CR), and normalized values for each criteria. Finally decision is taken if the calculated max. eigenvalue, CI, and CR are satisfactory. The consistency of the judgments is checked on the basis of consistency ratio (CR) which should be less than 0.1 [38]. The advantage of AHP is to find priority weights through paired comparison of attributes through a qualitative and quantitative approach [39].

## 4. Wind Farm Cluster Performance

In the present work, an attempt is made to evaluate the windmill cluster performance through multicriteria approach. The index to measure the performance is termed as CIOP-Cluster Index of Performance. The usage of energy is closely associated with human activities as well as sustainability issues and hence an energy system can provide lead indicators for sustainable development [40]. The selection of indicators is the primary step in wind farm cluster performance. Several studies have been carried out in the past using various MCDM methodologies such as AHP, VIKOR, fuzzy, and axiomatic design method, on assessment of sustainability indicators [33, 41]. The chosen indicators in the present work include technical, economic, environmental, and social components.

The evaluation criteria considered under each indicator are presented below:

(i) *Technical.* Energy production capacity, feasibility, risk, duration of preparation and implementation

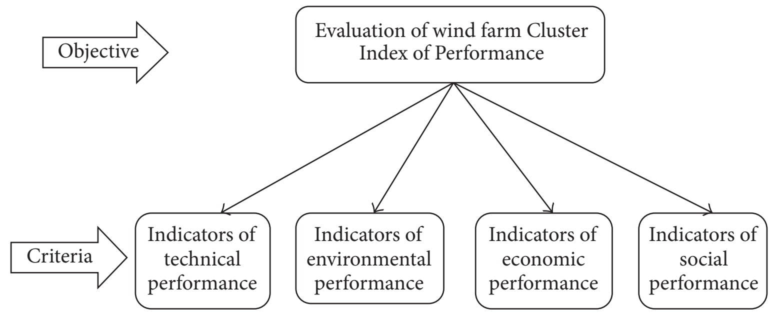


Figure 3: AHP framework for fixing weights of the criteria.

phase, technological maturity, reliability, safety, and local technical knowhow

(ii) *Economical*. Investment cost, implementation cost, operation and maintenance cost, service life, economic value (PW, IRR, and PBP), availability of funds

(iii) *Environmental*. Pollutant emission ($CO_2$), need of waste disposal, land requirements

(iv) *Sociopolitical*. Social acceptability, policy objectives, labour impact, political acceptance, and compatibility with national energy

Stakeholders involved are engineers working in wind farms, wind farm developers, Government officials from energy department, and a few selected residential people near the wind farms. To obtain the relevant data in each wind farm, the stakeholders are consulted through a set of structured questionnaire. The data varied from cluster to cluster and also between WTGs within a cluster. The proposed index for measurement of performance (CIOP) consists of four different criteria as shown in Figure 3. A total of 10 parameters were considered for each criterion including five subject oriented and five objective question-responses. The methodology is implemented by collecting empirical data from the wind-mill clusters located at Chikkodi, Saundatti, Raibag, and Belagavi in the Belagavi district of Karnataka which has been chosen for study.

*4.1. Criteria for Evaluating Wind Farm Cluster Performance.* Though there are many parameters relevant in evaluating the performance of wind farms, a proper methodology comprising important factors is required to be developed to estimate the wind-mill cluster performance. The following four indicators, namely, technical, economic, environmental, and social indicators, to evaluate the performance of a wind farm were recommended by the World Energy Council (WEC). Further, a total of ten parameters under each of the four proposed indicators were considered in this work to take into account various dimensions of each indicator. Out of these parameters, five are quantitative in nature and remaining five are qualitative response types.

*4.1.1. Indicators of Technical Performance (ITeP).* The total energy generated during the nominal period to the total potential energy that can be generated during the same period is termed as capacity factor (CF) and is measured in %. The amount of energy generated during the nominal period to the swept rotor area is represented by specific energy production (kWh/m$^2$). Equivalent full load hours are the availability of number of annual hours of WTGs. The plant availability factor represents the total operating hours of wind plant during the period to that of total length (in hrs.) of operation of each WTG in wind farms. The wind conditions data is very important to decide type and rating of WTGs that can be installed in any wind farm as it depends on the wind velocity and WPD of a particular region. The topography factor deals with the viability of installing different rating and type of WTGs, based on the topography and siting of them. The design aspect and its appropriateness in the cluster are measured using the factor, Development of Appropriate Design Criteria, Specification & Standards. The factor, full scale testing prior to commercial introduction, needs the real groundwork to be carried out in order to manufacture components of WTG as per the design criteria and standards, and it should also be tested prior to the practical implementation. The last two parameters (condition monitoring system and power evacuation) are very important to maintain sustained amount of power generation in the wind farm and its evacuation to the nearby grid to ensure economic feasibility. While the first five parameters values are obtained through quantitative computations the subsequent five parameter values are obtained on a 1–5 scale using stakeholder responses and value judgments. These parameters which contribute to the ITeP and the scores for the clusters under study are shown in Table 2.

*4.1.2. Indicators of Economic Performance (IEcP).* The parameters under economic performance criteria (IEcP) and the corresponding score are presented in Table 3. The turnover ratio is the ratio of total annual revenue generated to the total initial investment including WTG cost and up to grid connection cost. Internal rate of return (IRR) is the interest rate at which net present worth (NPW) becomes zero. Payback period (PBP) is the minimum time for any investor to get back his investment, if it is less this means the investor comes forward to invest more in WETs. Labour productivity is measured in terms of total annual revenue generated to the total annual expenditure on Human Resources (HR). Maintenance charges cover expenses towards annual Operation

Table 2: Comparison of the wind farms based on technical performance indicators (ITeP).

| Sl. number | Parameters | Wind farm location | | | |
|---|---|---|---|---|---|
| | | Chikkodi | Saundatti | Belagavi | Raibag |
| 1 | Capacity factor (CF in %) | 29 (2.70) | 27.95 (1.0) | 28.06 (1.18) | 30.42 (5.0) |
| 2 | Specific energy production ($kWh/m^2$) | 4741.1 (5.0) | 2425.99 (1.63) | 1994.19 (1.0) | 2436.16 (1.64) |
| 3 | Equivalent full load hours (hr) | 2541 (2.70) | 2449 (1.0) | 2458 (1.17) | 2665 (5.0) |
| 4 | Plant availability factor (in %) | 95.6 (2.95) | 95.75 (3.44) | 95 (1.0) | 96.23 (5.0) |
| 5 | Wind resources or wind conditions (velocity) during the period (in m/s) | 6.5 (5.0) | 6 (2.33) | 5.75 (1.0) | 6.2 (3.40) |
| 6 | Topography & sighting of wind turbines (WTG rating and type) | High (4.0) | V. high (5.0) | Medium (3.0) | Medium (3.0) |
| 7 | Development of appropriate design criteria, specification & standards | High (4.0) | Medium (3.0) | V. high (5.0) | Medium (3.0) |
| 8 | Full scale testing prior to commercial introduction | High (4.0) | High (4.0) | High (4.0) | High (4.0) |
| 9 | Condition monitoring system for turbine maintenance (O&M etc.) | High (4.0) | High (4.0) | High (4.0) | High (4.0) |
| 10 | Power evacuation (up to the grid) | V. high (5.0) | High (4.0) | Low (2.0) | Low (2.0) |
| | Total (score × weight of ITeP) | 18.488 | 15.376 | 12.212 | 18.849 |

Note: the number inside the () parentheses indicates the values of the parameters on a 1–5 scale. V.: very.

Table 3: Comparison of the wind farms based on economic performance indicators (IEcP).

| Sl. number | Parameters | Location of wind farm | | | |
|---|---|---|---|---|---|
| | | Chikkodi | Saundatti | Belagavi | Raibag |
| 1 | Turnover ratio | 15.39 (5.0)* | 7.8 (1.0) | 10.84 (2.60) | 8.9 (1.58) |
| 2 | Internal rate of return (IRR, %) | 14.67 (1.0) | 14.97 (1.68) | 15.59 (3.08) | 16.44 (5.0) |
| 3 | Payback period (PBP, in years) | 6.03 (5.0) | 5.68 (2.41) | 5.7 (2.56) | 5.49 (1.0) |
| 4 | Labour productivity | 870.99 (5.0) | 699.47 (2.87) | 548.56 (1.0) | 577.23 (1.23) |
| 5 | Maintenance charges (crores of Rs.) | 4.97 (3.08) | 5.74 (1.05) | 5.76 (1.0) | 4.24 (5.0) |
| 6 | Site factor (wind speed distribution) | V. high (5.0) | High (4.0) | Med. (3.0) | Med. (3.0) |
| 7 | Variation in annual energy output | High (4.0) | High (4.0) | High (4.0) | High (4.0) |
| 8 | Feed in tariffs (FIT) | V. high (5.0) | High (4.0) | Med. (3.0) | Med. (3.0) |
| 9 | Situations favorable for repowering | Medium (3.0) | Low (2.0) | V. low (1.0) | Low (2.0) |
| 10 | Accessibility to the wind cluster | High (4.0) | Low (2.0) | Medium (3.0) | Low (2.0) |
| | Total (score × weight of IEcP) | 6.53 | 4.08 | 3.98 | 4.53 |

*Note: the number inside the parentheses indicates converted parameter on a 1–5 scale.

& Maintenance (O&M) of WTG and accessories in order to keep up the machine availability to the maximum extent. As the variation of wind velocity and its distribution leads to the variation of annual energy output of any wind farm, it is captured in the form of site factor. Increase in feed-in tariffs (FIT) attracts the investors and motivates them to invest more. Favorable situation should be created in order to support the chance of repowering, if any, in the wind farm. Final parameter is an important economic aspect since the good accessibility to the cluster saves time, money, and so forth.

*4.1.3. Indicators of Environmental Performance (IEnP).* The various parameters covered under the environmental criterion (IEnP) and the corresponding score are shown in Table 4. First two parameters indicate the contribution made to the reduction of greenhouse gas (GHG) emissions concentrating on the major pollutant $CO_2$, on an annual basis, and other emissions like $NO_x$ and $SO_x$, along with $CO_2$ for the whole life cycle of WTGs. The third parameter considers minimum distance of WTG away from dwellings while the fourth is about the noise from WTGs. The fifth parameter records the number of birds killed during the development and maintenance of wind farm and the sixth is about shadow casting to nearby residence. Third, fourth, and sixth parameters capture the safety aspects by maintaining minimum distance away from nearby dwellings to avoid landscape, sound, and shadow flickering. Seventh, eighth, and ninth parameter indicate the importance of protecting historical heritage and environment by assessing wind farm's

Table 4: Comparison of the wind farms based on environmental performance indicators (IEnP).

| Sl. number | Parameters | Wind farm location | | | |
|---|---|---|---|---|---|
| | | Chikkodi | Saundatti | Belagavi | Raibag |
| 1 | Contribution to the reduction of GHG emissions (avoided $CO_2$ in t/mW/y) | 189700 (5.0) | 165000 (3.6) | 120800 (1.1) | 119100 (1.0) |
| 2 | Pollutant emissions during life cycle; $Q_{CO_2}$, $Q_{SO_x}$, $Q_{NO\,x}$ (t/kWh) | 1853.48 (5.0) | 1488.47 (2.87) | 1167.33 (1.0) | 1228.35 (1.36) |
| 3 | Visual effects/landscape protection distance (minimum distance away from dwellings in m) | 1350 (2.4) | 2000 (5.0) | 1000 (1.0) | 1100 (1.4) |
| 4 | Noise from wind turbines (in dB) | 49.6 (4.80) | 49 (5.0) | 57 (2.33) | 61 (1.0) |
| 5 | Birds fatalities (number of birds killed/WTG/Yr. n/yr) | 3 (1.0) | 1 (5.0) | 2 (3.0) | 2 (3.0) |
| 6 | Shadow casting to nearby residence (number of hrs/yr when the nearby dwellings suffer from shadow casting) | V. low (5.0) | Medium (3.0) | Low (4.0) | Low (4.0) |
| 7 | Archaeological and historical heritage | Low (2.0) | High (4.0) | Medium (3.0) | Low (2.0) |
| 8 | Hydrological assessment | Low (4.0) | Medium (3.0) | Medium (3.0) | V. low (5.0) |
| 9 | Assessment of flora and fauna/climate change (e.g., danger caused to species, migrating birds) | V. low (5.0) | Medium (3.0) | Low (4.0) | Low (4.0) |
| 10 | Interference with telecom. systems | Low (4.0) | Medium (3.0) | Low (4.0) | Low (4.0) |
| | Total (score × weight of IEnP) | 3.13 | 3.07 | 2.16 | 2.11 |

effects on flora and fauna, climate change, and so forth. Final parameter is relevant when the wind farm is nearby the dwellings where there is interruption for communication systems like mobile towers, antennas, and so forth.

*4.1.4. Indicators of Sociological Performance (ISoP).* Table 5 shows the ten parameters which are used in evaluating the sociological performance (ISoP) of a wind farm along with the score for the clusters. First parameter considers the number of jobs that a wind farm can generate from the manufacturing to the erection and commissioning stage and also during maintenance. Number of households electrified due to the development of wind farm is covered in the second parameter. Third parameter is very important for the smooth functioning and development of wind energy farm activities by ensuring safety. Fourth parameter is vital for landowners and nearby villagers who have given land for setting up the wind farm. Fifth parameter deals with the contribution made towards educational and cultural development of locality. Sixth parameter considers the degree of improvement in tourism due to the attraction of wind farm. The degree of damage caused by wind farm to nearby environment, people, and so forth is covered by the seventh parameter. The last three parameters try to figure out the positive effect of wind farm on the development of agricultural and rural industrialization, poverty alleviation, and migration/birth rates of nearby people.

## 5. Evaluation of Cluster Index of Performance (CIOP)

Different performance indicators have been used in this work to compare the performance of the different wind clusters. This is accomplished by developing an index to evaluate the performance called "Cluster Index of Performance (CIOP)". As presented in Section 3.3, Analytic Hierarchy Process (AHP) under multicriteria framework is used as a tool to evaluate CIOP. The advantage of AHP is that it helps to develop a theory and then provides a methodology for modeling the unstructured problems in the economic, technical, social, and management sciences [37]. By its flexible and powerful weighed scoring decision making process, AHP helps to set priorities and makes the best decision when both qualitative and quantitative aspects of a decision need to be considered [38]. AHP engages decision makers in breaking down a decision into parts, proceeding from the goal (at the top level) to criteria (at the subsequent level). The decision makers then make simple pairwise comparison judgments through the hierarchy to arrive at overall priorities for the criteria [42].

*5.1. Cluster Performance Analysis under the AHP Framework.* A cluster performance analysis framework is developed in this section utilizing the existing literature pertaining to the performance analysis and discussion with experts in the field

Table 5: Comparison of the wind farms based on sociological performance indicators (ISoP).

| Sl. number | Parameters | Wind farm location | | | |
|---|---|---|---|---|---|
| | | Chikkodi | Saundatti | Belagavi | Raibag |
| 1 | Jobs created by the plant (number of direct/indirect jobs created by 1 MW WTG at different stages, like manufacture, installation, O&M) | 7588 (5.0) | 6600 (3.6) | 4832 (1.1) | 4764 (1.0) |
| 2 | Providing access to electricity (number of households/ number of people having now access to the electricity produced by a 1 MW plant) | 180 (5.0) | 140 (3.40) | 90 (1.40) | 80 (1.0) |
| 3 | Industrial Safety Accident Rate (SAR) | 1 (5.0) | 3 (1.0) | 2 (3.0) | 2 (3.0) |
| 4 | Monetary benefit to the landowners lakhs Rs. per acre of wind farm (for leased lands, in % annual revenue) | 1.5 (1.43) | 4 (5.0) | 2 (2.14) | 1.2 (1.0) |
| 5 | Contribution made to the educational/cultural development of the local area (in terms of % annual revenue) | 2.2 (5.0) | 2 (4.16) | 1.25 (1.0) | 1.5 (2.05) |
| 6 | Degree of improvement in the tourism development | High (4.0) | Medium (3.0) | High (4.0) | Medium (3.0) |
| 7 | Extent of social costs (environment damage caused to people, etc.) | Very Low (5.0) | Medium (3.0) | Low (4.0) | Low (4.0) |
| 8 | Positive effect on agricultural production & rural industrialization | Medium (3.0) | Low (2.0) | Very Low (1.0) | Low (2.0) |
| 9 | Positive effect on incomes and poverty alleviation | Medium (3.0) | Medium (3.0) | Low (2.0) | Medium (3.0) |
| 10 | Positive effect on migration and birth rates of labour due to the wind farm | Medium (3.0) | Medium (3.0) | High (4.0) | Low (2.0) |
| | Total (score × weight of ISoP) | 10.31 | 9.32 | 5.48 | 5.12 |

Table 6: Pairwise comparison of criteria with respect to the goal.

| Criterion | IEcP | ITeP | IEnP | ISoP | Priority |
|---|---|---|---|---|---|
| IEcP | 1.000 | 0.333 | 2.500 | 0.505 | 0.163 |
| ITeP | 3.000 | 1.000 | 4.505 | 3.759 | 0.523 |
| IEnP | 0.400 | 0.222 | 1.000 | 0.300 | 0.082 |
| ISoP | 1.980 | 0.266 | 3.330 | 1.000 | 0.232 |
| Consistency index CI = 0.07806 | | | | | |

of wind energy. Four important criteria are considered to obtain the CIOP. The framework is prepared in a hierarchical structure, as the analysis is carried out using the multiple-criteria under AHP (Figure 3). It has two levels comprising the goal and criteria. Level 1 is the main goal which can be obtained by summating the scores of four performance indicators. Prior to this, the relative importance/priority of the four performance indicators (level 2) are obtained with respect to the goal (CIOP) through pairwise comparisons using AHP. The values in Table 6 represent the pairwise comparisons for the wind farms and are obtained by computing means of all the individual pairwise comparisons of responses from various stakeholders from each wind farm. Subsequently, by dividing each matrix element by the sum of respective column elements (normalization of column) and then by calculating the arithmetic mean of each row the priority is obtained. It is clear from Table 6 that the stakeholders give maximum priority (52%) to ITeP followed by ISoP (23%). The IEcP (16%) and IEnP (8%) get the next two positions. It is an established fact that technical performance is the most important aspect in deciding the cluster performance of a wind cluster and the same is reflected by the stakeholders. Economic aspects are rated as the third most important criteria followed by social factors. Low weight of the environmental factor indicates the least orientation of the stakeholders towards environmental performance indicators, as most of the WTGs in the selected wind farms are in barren hilly regions.

*5.2. Calculation of CIOP and Comparison of the Wind Farms.* All the four selected clusters were evaluated using the four performance indicators separately and results are shown in Tables 2, 3, 4, and 5. Among these parameters, the first five are quantitative ones and the last five are qualitative in nature. Since all the ten parameters were having different units, getting a total score becomes difficult as they cannot be added.

Table 7: Comparison of the wind farms based on CIOP.

| | Wind farm location | | | |
|---|---|---|---|---|
| Performance indicators | Chikkodi (CKD) | Saundatti (SND) | Belagavi (BGV) | Raibag (RBG) |
| IEcP | 6.533 | 4.077 | 3.977 | 4.533 |
| ITeP | 18.488 | 15.376 | 12.212 | 18.849 |
| IEnP | 3.132 | 3.073 | 2.159 | 2.112 |
| ISoP | 10.308 | 9.317 | 5.484 | 5.116 |
| *Total* | *38.461* | *31.842* | *23.833* | *30.610* |

To make quantitative values compatible with qualitative parameters, the quantitative values are converted into a scale of 1–5. Finally, to get the total score under the criteria, the sum of the ten values inside the parenthesis is multiplied by the weight of the respective criterion. Table 7 presents the final performance index, that is, the CIOP score of the wind farms. From this table it is evident that the Chikkodi wind farm cluster is the best performing cluster with CIOP of 38.46 followed by Saundatti, Raibag, and Belagavi clusters.

Wind energy has been used for many thousands of years, but only in the past 35 years it has come on a significant scale to be integrated into the modern energy supply. Research and development has already helped greatly to reduce the cost of wind energy, although there is scope to further lower capital costs, improve reliability, and expand the range of applicability of wind energy systems. To maximize the usage of this technology, proper sites should be investigated and wind turbines should be installed. Wind energy can play a significant role in strengthening the energy security of a country by decreasing the energy dependency, avoiding greenhouse gas emissions and by creating thousands of jobs.

## 6. Conclusions

It is foreseeable that the move towards generating electricity from renewable wind resources will become the trend in future years. There is a strong relationship between the availability of energy and economic activity of a country. Multicriteria decision making methods are becoming popular in helping governments and companies in evaluating energy sector plans, policies, projects and site selections issues, and so forth. Wind energy is a major source of power in over 70 countries globally. There is a huge and growing global demand for wind power, which can be installed quickly and virtually everywhere in the world.

Considering wind farm clusters as power plants comprised of multiple wind turbines, the current study focused on the determination of the best performing wind cluster. The primary focus was to develop a methodology to evaluate the performance of a wind farm cluster using multicriteria approach. Performance estimation among clusters has been made using AHP methodology. The proposed methodology develops an index of performance to evaluate the best performing wind farm cluster based on multicriteria decision making. Four evaluation criteria were taken into consideration according to the given literature, namely, technical, environmental, economic, and social indicators for development of Cluster Index of Performance (CIOP). Both qualitative and quantitative parameters were considered. The results of analysis suggest that the Chikkodi wind farm cluster as the best performing one, followed by Saundatti, Raibag, and then Belagavi farm. In the future research other multicriteria decision making techniques such as TOPSIS, VIKOR, and ANP can be used and their results can be compared with the proposed methodologies. This study has several notable strengths. First, in this study the qualitative factor in decision making process transformed to quantitative factors. Second, the survey is made by face to face to reduce questionnaire mistakes. Also, this study has certain limitations. First, data are taken from a small group in energy sector and the results in this study cannot be generalized. Second, the index may change by adding other clusters.

## Appendix

## A. Indicators of Technical Performance

(a) Capacity factor (CF in %) = total energy production during the normal period/potential energy production during the period

(b) Specific energy production (kWh/m$^2$) = total energy production during the normal period/swept rotor area

(c) Equivalent full load hours (h) = annual energy production/rated power

(d) Plant availability factor (in %) = total hrs. of operation of plant during the period × 100/total length of the period (hrs.)

(e) Wind resources or wind conditions during the period (in m/s)

While the first five parameters values are obtained through quantitative computations the subsequent five parameters are obtained on a 1–5 scale using stakeholder responses and value judgments. This analysis varies with each cluster.

## B. Indicators of Economic Performance

(a) Turnover ratio = annual revenue (Rs in crores)/total investment including WTGs and grid connections

(b) Internal rate of return (IRR) is the interest rate at which NPW becomes zero, that is, the value where the NPW curve crosses the interest axis in a NPW with time plot

(c) Payback period (PBP) = initial investment/(annual revenue – O&M charges)

(d) Labour productivity = annual revenue/annual HR expenditure

(e) Maintenance factor = annual revenue/annual O&M cost

For environmental and sociological indicators required data is directly collected from wind cluster site through questionnaire.

## C. Indicators of Environmental Performance

(a) Contribution to the reduction of GHG emissions (avoided $CO_2$ t/MW/y)

(b) Pollutant emissions during life cycle; $Q_{CO_2}$, $Q_{SO_x}$, $Q_{NO_x}$ (g/kWh) = quantities of $CO_2$, $SO_x$, and $NO_x$ emitted per kWh during the whole life cycle of the plant

The above parameters are evaluated by considering the data that 1 MW of power generation from coal thermal produces 19 ton of $CO_2$, 136 kg of $SO_2$, 7 ton of fly ash, and 60 kg of particulate matter per day, assuming an average plant load factor (PLF) of 75% [43].

## D. Indicators of Sociological Performance

(a) Jobs created by the plant: number of jobs created by 1 MW capacity WTG at different stages including manufacturing, installation, O&M period, and so forth

(b) Providing access to electricity: number of households having access to the electricity produced by a 1 MW plant

(c) Industrial safety accident rate (SAR): number of accidents for all utility personnel assigned to plant.

## Competing Interests

The authors declare that they have no competing interests.

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