1. Introduction

The Lake Turkana wind farm is one of the largest wind farm projects to be realised in the African Continent, and the first of its kind in Kenya. After its full commissioning in 2012, the wind farm will be generating 300 MW of clean power almost steadily thanks to the very peculiar characteristics of the wind climate of north-western Kenya. Until now, only northern African countries such as Morocco and Egypt had used wind power for commercial purposes on the continent. Projects are now beginning to bloom south of the Sahara as governments realise that harnessing the vast wind potential can efficiently meet the growing demand of electric power. With the Lake Turkana wind farm project and other minor projects, Kenya is trying to lead the way. The project consists of building 365 wind turbines Vestas V52 of hub height 45 m and nominal power 850 kW, corresponding to about 30% of Kenya’s current installed power. The project includes also reinforcing 200 km of roads and bridges to transport the wind turbines from the Indian Ocean port of Mombasa to the north-western Kenya, and adding more than 400 km of transmission lines and several substations to connect the wind farm and supply power to the national electric grid.

Behind the Lake Turkana wind farm project1 there is a consortium of Kenyan and Dutch based companies and persons, who asked DEWI GmbH to perform the site-related wind potential analysis and energy yield assessment of the whole wind farm. This would be a very challenging task for whatever leading company operating in the wind energy sector, as the wind climate of the area where the Lake Turkana wind farm is supposed to grow, is really unusual. The wind farm is located over an area that is almost unique in the world from the meteorological and geographical point of view, because the winds sweeping this region start something like 500 km far southeast in the Indian Ocean and are channelled through the “Turkana-Marsabit Corridor” created by Ethiopian and Kenyan highlands. This behaviour is due to the fact that Kenya is mainly subject to two monsoon wind currents, known as East African Monsoons, which are usually located over the ocean and are responsible for the seasonal weather conditions over the country (see Section 2). These synoptic-scale circulations interact with the local orography to generate some convergence zones. The low-level Turkana jet stream, which blows steadily during the whole year in the low elevation region of the Turkana-Marsabit Corridor, occurs in one of the most interesting (for wind energy exploitation) of these convergence zones.

1 www.laketurkanawindpower.com
The commonly adopted approaches for wind energy yield assessment are doomed to fail in this particular context as they are usually based on local-scale climatologies and rather small wind farm extensions compared to the Lake Turkana wind farm project. The methodology needed to manage this kind of complexity has to be able to take into account the aforementioned synoptic meteorological and orographical forcing, as well as the frictional effects of the local-scale topography and roughness on the wind flows within the wind farm area. Following these considerations, DEWI adopted a methodology based on the coupling of the mesoscale meteorological model MM5 with the local-scale model WAsP. The coupling between the two models is performed following a statistical approach based on two steps (see Section 3).

The final results, reported in Section 4, depict a wind farm with a long-term average wind speed of more than 11.5 m/s at the hub height of 45 m above ground level, and a gross energy production that almost reaches 2.000 GWh per year. Based on these estimations, the project is foreseen to reduce carbon emissions by 16 million tons during a 20-year lifespan.

2. Lake Turkana Wind Climate

From a climatological point of view, Kenya lies in one of the most complex regions of the African continent. Its synoptic-scale climate is mainly influenced by the superposition of the Inter Tropical Convergence Zone (ITCZ), which moves south and north of the equator following the seasons, and the thermal-driven circulation associated to the East African monsoons, mainly occurring over Kenya, Tanzania, and Uganda.

The East African monsoons are sometimes considered mere extensions of the much more well-known South Asian monsoonal system, and the East African and South Asian monsoonal systems are strongly connected indeed. The term “monsoon” derives from the Arabic mausim, which means season, and straightforwardly it was adopted to describe seasonal wind flows (see here 2). It is worth noting that this term was firstly applied to the wind all over the Arabian Sea, which blows for six months from northeast and for six months from southwest, so that the distinction between Asian and East African system was originally misunderstood. The East African monsoons, however, are phenomenologically different from the Asian monsoons as they are characterised by some peculiarities which make

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2 www.amsglossary.allenpress.com/glossary/
them very unusual with respect to typical monsoonal regimes. The most important of these is the relative dryness of both the North and South monsoon, caused by a prevalent divergence at low levels, as shown in Fig. 1 (after Nieuwolt, 1979). During the intermediate seasons between the monsoons, which are rather short and with highly variable onset, this divergence is temporarily replaced by the ITCZ.

A semi-permanent low pressure cell centred over Lake Victoria forces the main air-streams of both the monsoons, which are roughly parallel to the coastline over eastern Kenya, to flow zonally westward over north-western Kenya. This thermally-induced synoptic-scale deflection interacts with the orography of Eastern Africa to generate some convergence zones over the Ethiopian and Kenyan highlands. Just in between the Ethiopian and Kenyan highlands, the Turkana-Marsabit Corridor occurs, which is one of the windiest among these convergence zones. The channel floor is about 500 m above the mean sea level and has a depth that varies between 600 and 1500 m, and a width that varies between 150 and 700 km. The channel is approximately 700 km long and is oriented from southeast to northwest connecting north-western Kenya to southern Sudan. Fig. 2 shows the topography of the area around Lake Turkana. Within the Lake Turkana wind farm area (approximately 15 km southeast of Lake Turkana), three anemometric stations have measured the wind speed and direction at 45 m above the ground level. A LIDAR was also installed close to the mast in the central position. The position of masts and LIDAR is also shown in Fig. 2.

Firstly, Kinuthia and Asnani (1982) and Kinuthia (1992) observed the presence of the so-called Turkana low-level jet stream in this channel. They associated the presence of this jet, which flows steadily during both summer and winter monsoons and partially disappears only during intermediate seasons, to the branch of the monsoons that enters the Turkana channel and intensifies into the Turkana easterly low-level jet. In particular, in the passage between Mount Nyiru and Mount Kulal, the reduction of the flow section increases drastically the surface mean wind speed from 5-6 m/s in the centre of Chalbi desert up to more than 11 m/s at about 45 m a.g.l. Fig. 3 shows the wind rose calculated from almost two years of measurements recorded at the anemometric station MM265 (see Fig. 2). The picture clearly shows that the prevailing wind direction is ESE, the cumulated frequency of sectors E and ESE is greater than 93%, and the mean wind speed is 10.8 m/s at 38 m a.g.l.

3. Simulation Setup and Model-coupling Methodology

Indeje et al. (2001) employed the National Centre for Atmospheric Research regional climate model to study the dynamics of the Turkana low-level jet and investigate the
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role of different forcing factors in order to understand the kinematics of the jet. They found that the orographic forcing is the most important mechanism responsible for sustaining the jet, the large-scale monsoon background flow is important in determining the wind speed and jet cores, and the depth of the channel influences the vertical structure and location of the jet cores. Finally, they state that the frictional forcing at the surface plays a role equivalent to that of the large-scale monsoonal background winds in the formation and maintenance of the jet.

The latter conclusion of these authors is particularly important as it points out that the choice of the methodology to evaluate the wind potential of the Lake Turkana wind farm should be able to capture the synoptic-scale meteorological and topographical forcing as well as the local-scale frictional forcing. One methodology that should be able to satisfy this requirement consists of a multi-scale approach based on numerical models working at increasing resolution over smaller and smaller domains. This kind of zooming technique is quite common in numerical weather prediction and current mesoscale meteorological models can easily manage multiple domains through nesting techniques.

Meteorological models are general-purpose models. In principle, they can be used for whatever problem concerning atmospheric physics. They are not specific, however, for wind energy applications and the maximum resolution they can manage is of the order of one kilometre in their non-hydrostatic versions. For wind energy applications specific post-processing tools are needed and higher resolution are usually required. Following these considerations, DEWI adopted a methodology based on the coupling of the mesoscale numerical meteorological model MM5 with the local-scale model WASP.

MM5 is a numerical weather prediction model developed by the Pennsylvania State University and National Center for Atmospheric Research (PSU/NCAR) with the ability to simulate atmospheric conditions with resolutions ranging from 100 to 1 km. MM5 Version 3 (Grell et al., 1994) is a non-hydrostatic, prognostic model with explicit description of pressure, momentum and temperature (see also www.mmm.ucar.edu/mm5/mm5-home.html). The numerical solution is computed onto a rectangular-structured staggered grid by finite difference schemes. The vertical coordinate is terrain-following. The physical package of MM5 consists of a set of parameterization schemes for cumulus, radiation, planetary boundary layer, microphysics and surface processes.

MM5 requires a number of input data, in terms of initial and boundary conditions, to simulate the evolution of the atmosphere. These conditions concern both the geometry of the computational domains and the state of the atmosphere, described through the independent variables of the system. Elevation and vegetation cover derive from different datasets as described in Tab. 1, appropriately re-gridded to meet the resolution of the computational domains. The meteorological initial and boundary conditions used for the simulations were the National Center for Environmental Prediction (NCEP) Final Analyses (FNL). This data is provided by NCEP in GRIB format with a resolution of 1 × 1 degrees for the period from 2000 to present. FNL analyses are produced through the combination of the Global Data Assimilation System (GDAS) and the general circulation model AVN/GFS. Both systems are aimed to the best possible accuracy and constantly upgraded concerning observational datasets and data assimilation procedures.

MM5 simulations have been performed over four two-way nested domains with increasing resolution, from 27 km to 1 km, as shown in Fig. 4. MM5 setup is similar to that used by Jimenez et al. (2007). Twenty-seven terrain following levels have been used in the vertical direction, from 11 metres a.g.l. up to 50 hPa, the lowest 6 levels being below 100 m a.g.l. Tab. 2 shows the main properties of the computational domains. A total number of 122 simulations have been carried on for the period from 2009-01-01 to 2009-12-31. Each run consists of a hindcast of 78 hours, with 6 hours of spin-up period in order to allow the model
to develop high-resolution features over the inner domains. Also, the model’s solution is nudged towards the analysis in the outer coarser domain at each time step.

For the local-scale simulations, the computational model Wind Atlas Analysis and Application Program (WAsP), developed by the Wind Energy Division at Risø DTU, has been used (see also www.wasp.dk/Support/Literature.html). This is a program for the vertical and horizontal extrapolation of wind climate statistics (Troen and Petersen, 1989). It contains several models to describe wind flow over different terrains and close to sheltering obstacles. WAsP utilises the linear BZ-model (Bessel expansion on a Zooming grid) of Troen (1990) to calculate the wind velocity perturbations induced by orographic features such as single hills or more complex terrain. The BZ-model belongs to a family of models related to the Jackson and Hunt theory for flow over hills (1975), based on the resolution of the linearized equations of motion for neutral flow. The basic theory behind the model assumes the upstream wind speed to vary logarithmically with height, and flow perturbations introduced by the complex terrain are treated as small perturbations on the basic state wind profile. Theoretically, this should work only for small perturbations, but in practice a ratio of perturbations over basic flow up to about 0.5 still works well. It cannot calculate detached flow, however, so that in case of more complex terrain a different model, like a Computational Fluid Dynamics code, could be adopted.

According to Petersen et al. (1998), WAsP is mainly a wind climate model, and it is certainly the most widely used tool for wind energy resource assessment. In a standard project, a time series of wind measurements is firstly analysed to provide statistical summary of the observed, site specific wind climate. Then, the analysed wind data can be converted into a wind atlas data set or regional wind climate. In the case of Lake Turkana, however, the regional wind climate has been obtained by means of the MM5 simulations, and the wind atlas of the area under study has been evaluated taking into account a high-resolution description of the terrain.

The coupling between the two models is performed following a statistical approach based on two steps. Firstly, a number of joint probability distributions of the wind speed and direction evenly spaced over the whole wind farm area are obtained from the mesoscale model, and calibrated with the wind measurements at the three available anemometric stations (see next section). Secondly, the local model WAsP is applied with the aforementioned probability distributions as information for the wind climate over the wind farm area. This kind of approach allows evaluating the wind gradients induced by the large-scale meteorological and topographical forcing, which could exist within the wind farm area, also considering that three measurement masts are not enough to evenly cover such a big area.

4. Results

Results obtained through the procedure explained in the previous section have been verified by means of comparison with the available measurements on site. The measurements consisted of three anemometric masts installed in between Mount Kulal and Mount Nyiru, hereafter referred to as MM263, MM264, and MM265, and an advanced coherent doppler LIDAR (CRC-CARE, 2010). The position of all these instruments is shown in Fig. 2. Mast MM265 was installed in March 2008, whereas masts MM263 and MM264 were installed in October 2008. Uppermost wind speed and direction data were available at 46 m, 39 m, and 38 m above ground level for stations MM263, MM264, and MM 265 respectively. The LiDAR-system campaign was conducted over two periods in mid and late 2009, referred to as July and October campaign. The separation in time between the July and October campaigns provided an opportunity to examine the seasonal differences of meteorological conditions during winter and summer monsoon. In the following Section 4.1 a comparison between available measurements and simulations is presented. The validation refers to a period of time corresponding to approxi-
In 2009 and to the height of 45 m above ground level, i.e. the height of the chosen wind turbines. Finally, in Section 4.2 the results obtained from a simulation period of 1 year, from January to December 2009, properly scaled with long-term corrected measured wind data, are presented.

4.1 Comparison Between Measurements and Simulations

The LIDAR wind speed has been compared to the three mast measurements over two periods of time (11th – 24th of July and 12th of October – 7th of November, 2009) after removal of poor quality data. The LIDAR measures the radial wind field, with respect to its location, to a distance of approximately ten kilometres by means of a series of 360 degree horizontal scans. The LIDAR is “blind” for the first 500 metres along the laser beams due to electro-optical constraints within the receiver. Radial wind speed estimates were recovered from each beam at spatial resolution of 150 metres. The scans were configured to scan between -1 degree and 1 degree in vertical elevation in order to measure radial wind velocity data above and below 45 metre height across the landscape. Each scan took approximately 10 minutes to complete providing data consistent with the averaging period of the mast anemometers.

An advanced LiDAR data volume processing technique developed by the West Australian Department of Environment and Conservation was employed to retrieve the wind vectors. The technique categorises the available LiDAR data into several conical layers and subsequently subdivides each layer into many small analysis volumes. In each volume, an optimised wind vector is obtained after fitting through all data points included in the volume itself.

After each layer of the wind speed values is retrieved, the processing algorithm interpolates or extrapolates these values to 45 m above ground level assuming for the wind profile a power law under neutral atmospheric conditions. From the bi-dimensional field of the wind speed at 45 m a.g.l. obtained by LiDAR measurements, it turned out that the average ten minute wind speed on the relatively flat landscape to the east of the measurement domain is approximately 6 m/s. The average wind speed gradually increases as the flow moves westward to approximately 10 m/s near the LiDAR site. Maximum velocities occur on the higher ridges on the western boundary with wind speed reaching over 14 m/s.

The LiDAR mean wind speed values have been compared to the measurements of the top anemometers at the three mast locations. It turned out that the LiDAR has an almost systematic underestimation with respect to the cup-anemometer measurements, which leads to values of the mean wind speed of about 0.4% lower than mast MM263 measurements, 6.4% lower than MM265, and 5.2% lower than MM264. Following these considerations, a scaling factor has been calculated over the LiDAR scan area extrapolating the single-point factors through a Kriging algorithm.

The scaling factor has been applied to the original LiDAR measurements in order to correct the aforementioned bias and obtain a more reliable final estimation of the mean wind field at 45 m a.g.l. This final mean wind field has been compared to MM5-WAsP simulations for the same period of time.

Fig. 5 shows the percent error of numerical simulations with respect to the corrected LiDAR-measurements. Contours represent the orography over the wind farm area.
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(note that the LIDAR scan area extends farther to the east with respect to the eastern border of the wind farm area). The error is below 5% almost all over the scan area, apart from the southern part and some spots unevenly scattered around the LIDAR. This is an appreciable result if one considers that many sources of uncertainty exist both for LIDAR and numerical models, and that for this comparison model results are not “tuned” with any measurement. As far as the LIDAR is concerned, some uncertainties and biases in wind speed estimates are inherent to the instrument itself, in particular concerning the derivation of radial velocity, pointing accuracy, the interpolation/extrapolation scheme. An accurate radial velocity estimate is indeed crucial for a correct and coherent retrieval of the wind vectors. A typical profile of the signal-to-noise ratio during the Turkana campaign was characterised by values higher than -50 dB to a range of 6.5 km from the LIDAR, falling off to a level of -15 dB at a distance of approximately 12 km. This results in radial velocity accuracy between 0.6 m/s in a radius of 6.5 km from the instrument (blind area excluded) and 1.0 m/s in the far field. The pointing accuracy of the LIDAR beam is another critical aspect for a correct determination of the location of the wind speed measurement. A small error in the beam alignment will potentially results in a significant geographic area over a large distance from the LIDAR location. For example, an angle shift of 0.1 degree corresponds to a cross-range distance of 3.5 m at 2 km, 8.7 m at 5 km, and 14.0 m at 8 km from the instrument. Moreover, small changes in the alignment can occur over the course of a field deployment, which could reduce pointing accuracy. Finally, also the assumption (adopted for interpolation or extrapolation of wind data to the mast positions and to 45 m a.g.l. in the LIDAR grid points) that wind profiles follow a power law with exponent value typical of neutral atmospheric conditions is not completely proper when the terrain is not flat. This aspect might be one of the reasons of the larger discrepancies between model and measurements over the small ridges about 1 km W and SW, i.e. over mast MM265, or over the two steep valleys about 2.5 km NNW of the LIDAR location.

### 4.2 Lake Turkana Wind Potential Assessment

One year of numerical simulations, from January to December 2009, have been performed with the mesoscale meteorological model MM5. The statistical distributions of the time series of wind speed and direction at the three mast positions have been compared with the corresponding measured distributions, corrected for long-term de-trending with NCEP/NCAR Reanalyses data. Analogously to the comparison between LIDAR and mast measurements described in the previous section, three scaling factors have been obtained as ratio of the mean wind speed simulated and measured at the mast positions during the same period of time. Then, a map of scaling factors has been calculated over the MM5 inner domain extrapolating the single-point factors through a Kriging algorithm.

Now, a number of statistical distributions all over the MM5 inner domain, properly re-scaled according to the factors calculated in the previous step, have been obtained and used as input to the WASP model. The final map of the long-term annual mean wind speed calculated by WASP is shown in Fig. 6. It is worth noting that the strong horizontal wind gradient occurring along the south-east to north-west direction of the wind farm area over a distance of more than 20 km, which is also detected by LIDAR measurements (see Section 4.1), is due to the correct large-scale forcing imposed by the mesoscale model simulations. The three anemometric masts are located along a direction perpendicular to the main wind gradient, so that this forcing cannot be properly represented by the wind measurements obtained with the present mast layout. The application of WASP in a stand-alone configuration (not shown here) is not really able to capture the main wind gradient as it is not related to a local-scale forcing.

From final results presented in Fig. 6, the long-term mean wind speed averaged at the turbine positions turns out to be around 11.8 m/s at the hub height of 45 m a.g.l. These values, together with the unusually high values of the shape parameter of the Weibull distribution (see Fig. 3), determine also incredibly high values of the capacity factor, which is on average almost 70%. The exploitation of such a high wind potential also represents a challenge for the wind turbine manufacturer, who will face the problem of guaranteeing

<table>
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<th>Data type</th>
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<th>Original dataset resolution (deg)</th>
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<td>Land use</td>
<td>PSU/NCAR Land Use Data</td>
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<td>Soil</td>
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<td>Vegetation fraction</td>
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<td>Deep soil temperature</td>
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Tab. 1: Topographical data used to provide MM5's computational domains with the corresponding geometrical boundary conditions.

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<th>Resolution (km)</th>
<th>Number of grid points</th>
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<td>4</td>
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</table>

Tab. 2: Properties of the four computational domains used to perform MM5 simulations. x–, y–, and z–direction correspond to west-to-east, south-to-north, and upward directions, respectively.
wind turbines that are supposed to withstand steady strong winds during extreme temperature conditions.

5. Conclusions

The Lake Turkana wind farm project will require further development and new research in the future, as the uncertainty of the results presented in the previous section is still rather high. A range of issues should be studied more in depth, including for instance the remote sensing application to wind energy, how to compare measurements with modelling results, how to estimate model uncertainties. Although remote sensing is a very promising technique, caution is required in attempts to make direct comparisons between point source wind measurements technologies such as cup and sonic anemometers with those obtained from e.g. LIDAR or SODAR. There are fundamental differences between the technologies on how they achieve the measurement in terms of physical and optical processes, as well as spatial and temporal dimensions of the measurement domain employed. The same holds for numerical modelling, where differences in numerical schemes, atmospheric parameterisations, horizontal and vertical resolution, etc. make it really difficult to perform direct comparisons among different models and with measurements. These issues have been subject of many investigations over the past years by researchers with interests in wind climatology, boundary layer meteorology, turbulence, and wind energy applications. The Lake Turkana wind farm project is a clear example of how these issues can be inter-related and tightly connected each other.

References


