**Method for Estimating the Potential of Small Wind Power in the Urban Built Environment**

Matthias Haase¹, Christoph Nickl², Johannes Brozovsky³

¹School of Life Sciences and Facility Management, Zurich University of Applied Sciences, Wädenswil, Switzerland
²Team für Technik GmbH, München, Germany
³Architecture, Materials and Structures, SINTEF Community, Trondheim, Norway

**Abstract**

Our work proposes a method to enable quick estimates of local small wind power resources depending on the wind pattern in the higher atmosphere and the urban fabric. This will enable urban planners and city managers to simulate the potential of wind power as a local renewable energy source. The aim of this work was to develop a practical simulation approach for wind power in the built environment. Wind conditions were scaled down and urban fabric parameters introduced. Wind power calculations were set up and implemented in a GIS model and tested for a case study in the City of Munich.

**Highlights**

- Our work proposes a method to enable quick estimates of local wind power resources
- The method is based on a practical simulation approach for wind power in the built environment
- The method can be applied to any city grid and location

**Introduction**

Despite all the strategies, roadmaps, and the overarching goal to become the first climate neutral continent (European Commission 2021), the global energy crisis (IEA - International Energy Agency 2022) has made Europe and Germany in particular aware of the dependence on the imports of energy and fossil fuels from abroad. So far, mild weather has somewhat cushioned the severity of the crisis with regard to both energy prices and the use of gas, particularly from Germany’s national energy storages (Bundesnetzagentur 2023).

Besides solar, wind is the most promising renewable energy source. Both will account for about 90 % of the renewable power capacity added during the next five years globally (IEA - International Energy Agency 2023). Regarding wind, so far, focus has been on large-scale, onshore and increasingly also offshore wind farms in unobstructed and rather flat open spaces due to more favourable flow conditions. A disadvantage of remote windfarms however is the distance to the end user and thus high cost of providing the necessary infrastructure for long-distance transmission of electricity as well as roads for installing the wind turbines.

In urban areas on the other hand, a densely built-up environment, converting high speed laminar flow into a low speed turbulent flow, scarcity of space, and noise emissions have prevented a large-scale implementation of small-scale wind turbines (SWT) so far. However, high energy prices have made these more unfavourable locations increasingly attractive. It could enable households to become prosumers (consumers and producers) of electricity, by consuming self-produced electricity and sell surplus to the grid.

Geographical Information Systems (GIS) are commonly applied for site location identification in the wind energy sector, especially for large-scale wind farms e.g. (Díaz and Guedes Soares 2020; Latinopoulos and Kechagia 2015; van Haaren and Fthenakis 2011), but has also been used in urban areas (Gagliano et al. 2013).

This paper aims at developing a method for the assessment of urban environments. It is based on combining different attributes to identify the urban wind energy potential for a city. The method is further tested for the City of Munich, Germany. The approach includes the use of spatially referenced and publicly available GIS data, 1-km² gridded weather data from the German Weather Service (DWD) and technical specifications of small-scale wind turbines available on the market. From that, the energy yield potential, regulative practicability and economic feasibility is determined.

Similar work has been done by Millward-Hopkins et al. (2013) for the city of Leeds, UK. Assuming a minimum of 4 m/s, between 2,000 and 9,500 viable turbine sites in the urbanized area were identified. However, no concrete quantitative estimate for urban wind energy production or economic feasibility was reported. In addition, urban planning attributes (like e.g. noise regulations) have not been included. Thus we propose an assessment method that assesses in total 5 attributes for the urban wind energy potential.

The paper is structured as follows: Following the introduction, the method is described in detail. Then, the results are presented and discussed. Finally, the main conclusions and an outlook are given.

**Methods**

Since this work proposes a method to enable quick estimates of local wind power resources depending on the wind pattern in higher atmosphere and the urban fabric, it
combines information from different sources and datasets. The method is based on several attributes, namely city grid and location where atmospheric wind data and 3D-geometries of the building fabric are available. This is combined with technical data on SWT technology, geometric data and urban planning data.

**Attribute 1: Meteorological data**

The basis for estimating the wind potential are the publicly available test reference years provided by the German Weather Service (DWD). They provide climate data specific to a 1×1 km² grid for Germany (see also Figure 1). For this work, the test reference years for the present (Gegenwarts-Testreferenzjahre) with creation year 2015 are used. They are based on measurements and observational data from the years 1995 to 2012. The data for each grid cell is then calculated with different scale climate models, which also take largescale meteorological parameters and topography into account. These datasets are often used in building performance simulation as they contain hourly values on major climate parameters (Deutscher Wetterdienst and Bundesamt für Bauwesen und Raumordnung 2017).

For attribute 1, the focus was on the wind data provided, namely hourly average wind speed at a reference height (10 m above ground) and wind direction. To obtain the wind data for a whole city such as Munich, 326 datasets (1x1 km² grids) were used. For each dataset, average wind speed, main wind directions and velocity distributions are calculated using MATLAB and Microsoft Excel. As the wind data was only available at reference height, the wind velocity had to be transposed to different heights up to 60 m using equation (1), where \( U(z) \) is the wind velocity at height \( z \) [m/s], \( U(\text{ref}) \) is the wind velocity at reference height \( z_{\text{ref}} \) [m/s], and \( z_0 \) is the surface roughness height according to Wieringa (1992). As a result, hourly values at different heights are available.

\[
U(z) = U_{\text{ref}} \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{\text{ref}}}{z_0}\right)}
\]  

The wind speed distribution was calculated using a bin width of 0.5 m/s corresponding to the resolution of the power curve (Wand 1997).

**Attribute 2: Technical data and power curve**

The wind data is then combined with a power curve of a realistic and existing small wind turbine (Britwind R9000, see Figure 2). The available power curve is based on measured data from long-term monitoring necessary for the certification process in the “micro generation certification scheme” in the UK (see Figure 3). For each grid the possible yearly energy yield is then calculated at a different height using 5 m steps. A minimum roof height of 20 m was assumed for more or less acceptable wind conditions. An upper limit was not set and was, therefore, determined by the maximum building height.
representation in QGIS had to be created first. The roof areas were mapped to a specific grid according to their location and the grid ID was added as another attribute to the roof area (see Figure 4).

In a next step, the “attribute table” was exported to Microsoft Excel. There, the mapping of the values for yearly energy yield was done with respect to grid cell ID and roof height. If the roof height was between two existing values, the values were interpolated. It is possible to add further restrictions, such as only “flat roofs” with a minimum height above ground of 30 m.

**Attribute 4: Economic analysis**

In order to determine a threshold for an economical operation a lifecycle cost analysis based on VDI 2067 was carried out. The investment costs for a 5-kW wind turbine were estimated at 27,500 €, the additional costs for planning and assessments to 6,000 €. The yearly costs for operation were estimated at 550 €/a (2 % of investment).

Therefore, the total cost for 20 years of operation are around 55,750 €. In that time, the total amount of electricity produced differs with location and height.

In case of the wind data for the DWD Station 3379 “Munich-City” the electricity production costs range from 0.26 €/kWh (60 m) to 0.58 €/kWh (20 m). Depending on the electricity procurement costs and self-consumption rate different scenarios are economical. In case of 100% self-consumption and 0.28 €/kWh electricity purchase costs (from the grid), SWT sites with a yearly yield of 8,500 kWh are economically reasonable. Therefore, 8,500 kWh/a was chosen as a threshold.

**Attribute 5: Urban planning and regulations**

Despite the technical possibilities of small wind power, there are economical reasons and regulatory aspects in particular which are the main obstacle for wider use in the urban environment. Together with city officials in the Department of Immission Control, different datasheets of turbines were assessed. Most suppliers offer only insufficient data on noise emissions and if they do, they are often not independently measured.

In Germany, according to the German standard DIN 4109, the allowed noise level in front rooms with “special requirements” (for instance living rooms, nurseries, offices, classrooms, etc.) vary depending on the classification of area. Table 1 lists the night-time and the strictest requirements that might be applicable in certain cases for different types of areas. In Table 2, sound power levels for exemplary SWT are shown. It can be seen that they range between 77.7 dB(A) and 88.8 dB(A).

For a SWT (Amperius VK250, 80 dB (A)) the decline in sound power level with distance (no obstructions) was given by the manufacturer. According to the data, a distance of 10 m is needed in industrial areas, but up to 130 m in pure residential areas in order not to exceed the strictest thresholds in Table 1.

Consequently, for a SWT with a sound power level of 80 dB(A) a distance of 10 m is needed in industrial areas, but up to 130 m in pure residential areas (Leonhartsberger et al. 2019). A distance which is not often available in cities.
but is crucial for early-stage investigation and estimating the potential for an entire city. For the case of Munich and most municipalities, these areas are defined in a zoning plan and are publicly available. Again, the location of the "roof areas" was compared to the geometry of the areas and then added as another attribute.

However, the methodology followed in this paper does not consider if other zones according to the regulation “Technical Instructions for Protection against Noise” are in the vicinity and whether distances are respected accordingly. For example, an installation may be located in an industrial area bordering a general residential area. In this case, the installation must be at least 100 m away from the nearest residential building to comply with the limit values.

Table 1: Strictest requirements for different zones of an urban area.

<table>
<thead>
<tr>
<th>Type of zones/areas</th>
<th>Night</th>
<th>Strictest requirements in certain cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>70 dB(A)</td>
<td>64 dB(A)</td>
</tr>
<tr>
<td>Business</td>
<td>50 dB(A)</td>
<td>44 dB(A)</td>
</tr>
<tr>
<td>Core, village, and mixed</td>
<td>45 dB(A)</td>
<td>39 dB(A)</td>
</tr>
<tr>
<td>General residential</td>
<td>40 dB(A)</td>
<td>34 dB(A)</td>
</tr>
<tr>
<td>Pure residential</td>
<td>35 dB(A)</td>
<td>29 dB(A)</td>
</tr>
<tr>
<td>Hospitals, nursing homes</td>
<td>35 dB(A)</td>
<td>29 dB(A)</td>
</tr>
</tbody>
</table>

Table 2: Sound power level of exemplary SWT at 8 m/s wind (v = vertical-axis, h = horizontal-axis).

<table>
<thead>
<tr>
<th>SWT Name (Reference)</th>
<th>SWT Type</th>
<th>Nominal power</th>
<th>Sound power [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amperius VK 250</td>
<td>v</td>
<td>5.0 kW</td>
<td>80.2</td>
</tr>
<tr>
<td>Britwind R9000</td>
<td>h</td>
<td>5.0 kW</td>
<td>88.8</td>
</tr>
<tr>
<td>Hi Vawt DS-3000</td>
<td>v</td>
<td>1.4 kW</td>
<td>85.4</td>
</tr>
<tr>
<td>Tozzi Nord TN535</td>
<td>h</td>
<td>10 kW</td>
<td>84.8</td>
</tr>
<tr>
<td>Windspot 1.5</td>
<td>h</td>
<td>1.5 kW</td>
<td>77.7</td>
</tr>
</tbody>
</table>

It is therefore assumed that for the potential with regard to immission control, the pure and general residential areas are omitted, and the remaining areas can only be assessed with a maximum of 50%.

The installation area for SWT masts was estimated at approx. 50 m². In order to take additional roof structures into account, the roof areas should be at least 100 m². For determining the technical potential, it was assumed that 500 m² would be required for each additional installation on the same roof. This is because the turbines have to be at some distance from each other, otherwise they would be in each other's "slipstream". Especially if the turbines...
are behind each other in the main wind direction. This is in line with values for relative distances according to the rotor diameter from larger wind farms. Here, distances of up to 5–10 times the rotor diameter are assumed. In the case of the example turbine with a rotor diameter of 5.5 m, this would result in an area of 1,500 m². However, since turbine configurations can also be parallel if the geometry and orientation are appropriate, the estimated space requirement was significantly reduced.

Results

Technical and economic potential (attributes 1–4)

As shown in Figure 4, the majority of flat roofs are < 40 m above ground. For more or less acceptable wind conditions, a minimum height of 20 m and minimum area of 100 m² were assumed for the technical potential. For the City of Munich, the technical potential was consequently calculated at 27,000 MWh/a. Following the assumptions from the economic analysis, in which SWT systems were found to be just economical if they produce more than 8,500 kWh/a at electricity purchase costs of 0.28 €/kWh and 100 % self-consumption, a total of 257 roof areas are deemed economical. Thus, the economic potential was calculated at 3,700 MWh/a which corresponds to the electricity use of approximately 920 households.

Economic Potential with regard to immission control (attributes 4 and 5)

As described in the Methods section, immission control requirements are a major obstacle to the installation of wind turbines in urban areas. A precise assessment cannot be carried out within the scope of this study. Nevertheless, parts of the urban area can be largely assigned to the areas listed in the regulation “Technical Instructions for Protection against Noise” (TA Lärm) (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2017) based on the land use plan. An evaluation of the installations and their potential yield is shown in Table 3. Most of the technical potential is in general and pure residential areas (56 %), as they make up a large share of the city space. They are followed by core and mixed areas (27 %). However, the economic potential is higher in the core/mixed areas, indicating a higher share of suitable locations, i.e., higher buildings. Generally, the economic potential is only 14 % of the technical potential (see also Figure 5).

Figure 5: Annual electricity yield for economically viable SWT sites with the city’s zoning plan (Landeshauptstadt München - Referat für Stadtplanung und Bauordnung 2018) in the background.
A large part of the potential yield is located in areas with high noise protection requirements. In pure residential areas this is approx. 10% and in general residential areas 20% of the economic potential.

This results in a potential yield of 1,100 MWh/a for installations that are likely to be economically viable and eligible for approval. This corresponds to the electricity consumption of ca. 276 households or 0.0152% of the total electricity consumption of the City of Munich (Bayerisches Landesamt für Umwelt 2021). This amounts only to about 4.1% of the technical potential and 29.7% of the purely economic potential, not considering urban planning regulations and especially restrictions from immission control requirements.

**Discussion**

The results of the assessment for the City of Munich show a large potential for wind power in the City of Munich. Data of different attributes were collected and combined. E.g., wind characteristics were obtained from the meteorological service unit. Urban fabric data was provided by the local planning officials through GIS data. Wind urban fabric characteristics were used to calculate the wind power potential for the City of Munich. Urban planning regulations like view, noise and snow were collected and incorporated. Economic parameters were added. Thus, a realistic renewable power potential could be obtained. Although electricity prices in 2022 reached an all-time high which has significant influence on the number of economically feasible SWTs and the economic potential, prices stabilized again at pre-energy crisis levels. Therefore, no further analysis of the economic potential with regard to higher electricity prices was carried out.

There is a large potential for wind power in Munich. The results indicate those areas with the highest potential in industrial areas with (few) high-rise buildings. However, investment costs for wind power remain high. But with the current electricity prices, it is still a good investment with low payback periods.

It could be demonstrated that the new assessment method based on several attributes for SWT in urban context provides valuable information for the city/municipality. The five attributes that were introduced to the evaluation scheme allow for a more detailed evaluation of each attribute (meteorological, technical, geometric, economic, urban planning and regulation). The potential for SWT in the city is determined by wind data, technical data, geometric data, economic data as well as city planning data. Thus, it is important to use a method that combines these datasets of different attributes.

**Conclusions**

A method for early-stage assessment for SWT potential in cities was introduced. This is in an effort to balance the accuracy that is needed in early stages of assessment with computational power. It is based on information that can be divided into several attributes, namely city grid and location where atmospheric wind data and 3D-geometries of the building fabric are available, technical data on small wind turbine technology, geometric data and urban planning data.

In addition, it is based on publicly available data that is free of charge. By combining these attributes, an assessment can be done for SWT potential in cities which then can be included in the GIS system of the city This has several advantages:

- Low costs for the city/community
- Easy to assess for different stakeholders
- Integrated information on technical and urban planning aspects (energy production vs. noise regulations)
- The method described here can be fully automated using open-source software like QGIS.
- The method can be applied to all cities and municipalities that are interested

The assessment method was tested on the available GIS data of the City of Munich. The results are helpful for city administration in understanding the potential of SWT potential in its city boundary. This method based on five attributes provides valuable information and enables urban planners and city managers to simulate the potential of wind power as a local renewable energy source.

**Limitations and outlook**

The division into several attributes allowed to directly link datasets of information from different domains. These datasets have to be accessible. In different locations and countries these datasets will not necessarily be available.

Furthermore, the following criteria could not be included in the assessment of potential:

- Structural properties of individual buildings were not considered. Neither was vibration control (from wind turbine to the building structure).
- Detailed local windflow conditions at/around the individual buildings.

---

Table 33: Technical and economic potential for different areas listed in the regulation “Technical Instructions for Protection against Noise” (TA Lärm).

<table>
<thead>
<tr>
<th>Type of zone/area</th>
<th>Technical potential [kWh/a]</th>
<th>Economic potential [kWh/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>506,728</td>
<td>39,894</td>
</tr>
<tr>
<td>Business</td>
<td>1,832,816</td>
<td>222,226</td>
</tr>
<tr>
<td>Core-, Village-, und Mixed</td>
<td>6,413,141</td>
<td>1,786,562</td>
</tr>
<tr>
<td>General residential</td>
<td>7,587,834</td>
<td>642,718</td>
</tr>
<tr>
<td>Pure residential</td>
<td>5,519,184</td>
<td>307,815</td>
</tr>
<tr>
<td>Special</td>
<td>1,391,771</td>
<td>176,116</td>
</tr>
<tr>
<td>Supply and waste disposal</td>
<td>86,686</td>
<td>63,891</td>
</tr>
</tbody>
</table>
• Distances between buildings (e.g., for evaluating immission control).
• Actual space available on the roof (existing equipment) as this is case sensitive. Moreover, the shape of the roof in relation to the main wind direction was not considered in the GIS and remains a subject for future investigations.
• Account for different ground height in one grid cell.
• A rather general/basic economic feasibility analysis was carried out. Changes in energy prices over time can be expected and further work is needed to evaluate the robustness of these parameters.
• Not all urban planning regulations could be considered, e.g., distance from a location in one type of urban planning zone to a building in another zone.

Some of the limitations mentioned are planned to be taken into consideration a further work in the future. By that, the analysis could be refined, using more detailed wind data and integrate further details, if possible, on smaller grids. However, the results of the early-stage assessment are not meant to substitute detailed wind power engineering if a SWT is planned to be installed.

Future studies on urban wind power should also take combinations with solar power into consideration. Preliminary investigations have shown a significant potential of combining both technologies in urban areas.

Acknowledgement

Financial and technical support from the city of Munich is acknowledged.

References


Deutscher Wetterdienst (DWD), Bundesamt für Bauwesen und Raumordnung (BBR) (2017). Ortsgenaue Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse [Location-specific test reference years for Germany for average, extreme and future climate].


