

Assessment of the Impact of a Low-Rise Flat Roofed Building on Ambient Wind Conditions



Stefan Hübl, Mauro Peppoloni, Kurt Leonhartsberger
and Alexander Hirschl

Abstract Small wind turbines (SWT), representing a relatively new technology in the field of renewable energies, exhibit potential for a notable contribution to a sustainable urban energy supply accelerated by international climate agreements [1]. However, many uncertainties remain regarding site assessment, especially in the built environment. Wind conditions in areas below 30 m above ground, where small wind turbines are preferably installed, are affected by complex aerodynamic effects. Urban areas feature conditions often not considered by common CFD models and calculations. This paper focuses on the impact of low-rise flat roof buildings on the ambient wind flow. Contrary to other investigations on wind flow around complex obstacles relying on numerical fluid flow simulations or scaled wind tunnel experiments, the performed investigation relies on measurements over a flat-roofed building. The data acquired over a span of 7 months by several 3D-ultrasonic anemometers at the Lichtegg test site (Lower Austria) was examined. In order to determine the impact of the building on ambient wind conditions, the horizontal and vertical wind velocity, turbulence intensity and direction scatter at several locations were compared to the uninfluenced inflow conditions. Moreover, in addition to the commonly calculated horizontal turbulence intensity, the vertical turbulence intensity was considered to gain a deeper understanding for the occurring aerodynamic effects. The measurement results indicate that some locations on or around the building are not suited for installing wind turbines, while others show increased wind potential compared to undisturbed wind stream. Based on findings obtained by the wind assessment, recommendations for ideal placing of small wind turbines on low-rise buildings are given.

Keywords Small wind turbine · Urban · Building mounted · Site assessment · Micro-siting vertical turbulence intensity

S. Hübl (✉) · M. Peppoloni · K. Leonhartsberger · A. Hirschl
University of Applied Sciences, 1210 Vienna, Austria
e-mail: stefan.huebl@gmail.com

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1 Introduction

Small wind has the potential to act as a comprehensive supply of sustainable, renewable energy in urban areas, where it is generally not possible to install large wind turbines.

Unfortunately, most research related to wind energy has its roots in large wind research. However, some of those theories seem not to be applicable at low altitudes or in complex terrain where small wind turbines are mostly operated.

A special field of research in this context is the ideal location of installation on or around urban buildings. Some research has already been performed by other authors, who worked with 3D Computational Fluid Dynamics (CFD) simulations or based on 3D measurements of wind properties over two dimensional obstacles. Unlike these surveys, this investigation relies on an elaborated measurement set-up that was installed at Lichtenegg Energy Research Park, Austria to perform 3D measurements of wind properties.

What makes this series of measurements interesting is that measurements were performed both with undisturbed properties over open surface and with an installed flat roof obstacle in the wind stream. Thus, this setup allows a detailed analysis of both cases.

2 Measurement Set-Up

2.1 *Lichtenegg Energy Research Park*

Lichtenegg is located approximately 60 km south of Vienna, close by Wiener Neustadt. The area is located at a hilltop on the eastern foothill of the alps. The altitude of approximately 800 masl as well as its exposed location in the hilly range of the “Leithagebirge” makes it a location with comparably high wind speeds.

The surrounding area mainly consist of acres, while the surface of the measuring field is covered with grass and in further distance from the set-up (over 500 m) forest. The surface area is running slightly downhill in southern direction with $\Delta h = -1.8$ m.

As a result of the above described geographic conditions, the main wind directions are North-West and South. Below in Fig. 1 wind roses of measuring phase 1 (no obstacle in wind stream) and phase 2 (cubic obstacle in wind stream) are displayed.

The mean wind velocities for phase 1 and 2 are 4.41 and 4.54 m/s, while maximum wind velocities were measured at 18.39 and 19.35 m/s.

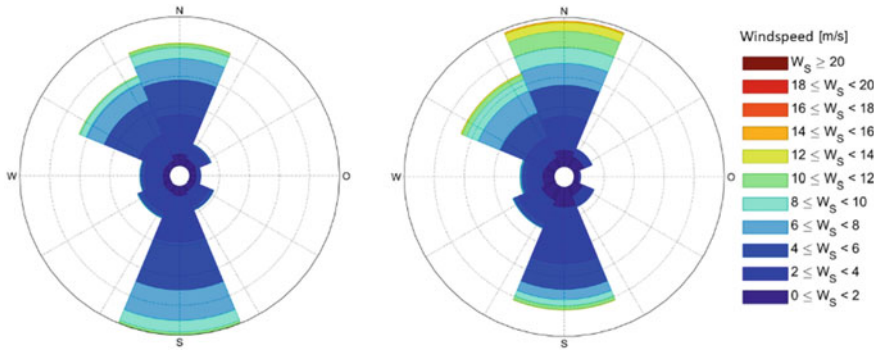
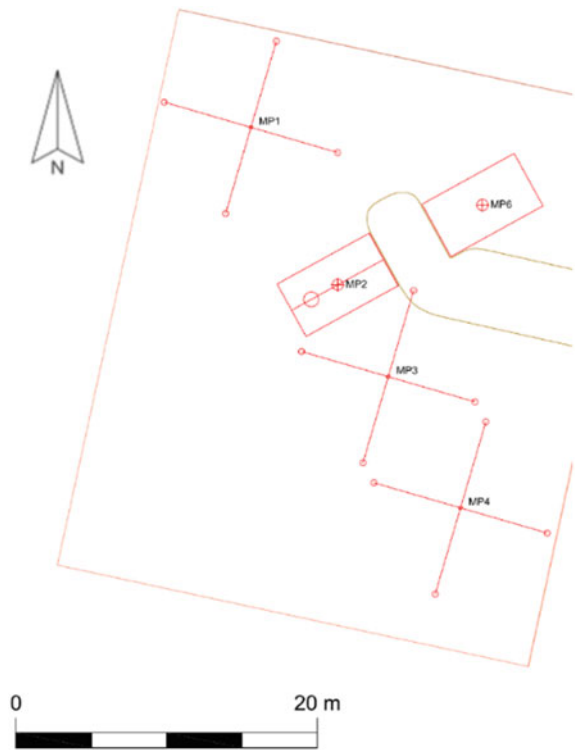


Fig. 1 Wind roses during measuring period. Left: phase 1, right: phase 2 [2]

Fig. 2 Orientation of set-up [3]



2.2 Set-Up

Four masts with measuring equipment in three different heights have been installed (MP1-MP4). Figure 2 shows the orientation of the masts and obstacle.

Table 1 Overview of measuring points

Measuring mast	Installation heights		Vertical wind speed measuring
	Phase 1 (m)	Phase 2 (m)	
MP1	10.5	10.5	No
	7	7	Yes
	3.5	3.5	No
MP2	10.5	9	Yes
	7	7	Yes
	3.5	5	Yes
MP3	7	7	Yes
	3.5	3.5	Yes
MP4	10.5	10.5	No
	7	7	Yes
	3.5	3.5	No

The masts are aligned with the main wind direction, North-South with a slight rotation of 28° in western direction. One Mast (MP1) is installed in the inlet flow (related to main wind direction) north of the obstacle. MP2 is installed on the building and MP3 and MP4 are supposed to capture the backlash of the wind flow after the obstacle. MP6, that is also displayed in Fig. 2, was not active during the measurements performed for this paper. This mast is installed for follow-up experiments over a pitched roof building.

MP1 is installed 15 m in front of the garage, MP2 is installed centered on the garage, MP3 is installed 5 m and MP4 15 m behind the garage.

Due to the reinstalling of MP2 for phase 2, the measuring heights of one of the sensors was slightly changed compared to phase 1. This change of heights is listed in Table 1.

Two different types of anemometers are used. On the one hand 3D-Ultrasound-anemometers, that also allow measurements of vertical wind speeds and on the other hand conventional cup-anemometers, that solely measure vertical wind speeds. An overview of availability of vertical wind velocities is given in Table 1.

Cup-anemometers used for the experiment exhibit an accuracy of measurement of ± 0.243 m/s according to calibration protocols, while for the ultrasound anemometers a precision of ± 0.01 m/s is expected.

The set-ups for phase 1 and 2 is displayed in Fig. 3. The obstacle analyzed within the experiment is a simple cubic garage building with dimensions of $6 \times 2.99 \times 3.35$ m (L \times W \times H).



Fig. 3 Measuring set-up phase 1 (left) and phase 2 (right) [4]

3 Measuring Execution

3.1 Data Basis

The data is collected continuously at a sample rate of 1 Hz for every measured property. The mean value over 60 s is calculated and stored internally by the data-loggers (two Ammonit Meteo 40 M), including standard deviation for every one-minute value generated in that manner. These one-minute averages serve as the base for all further calculations performed in Matlab. Processed properties are:

- Horizontal wind speeds
- Vertical wind speeds
- Wind direction

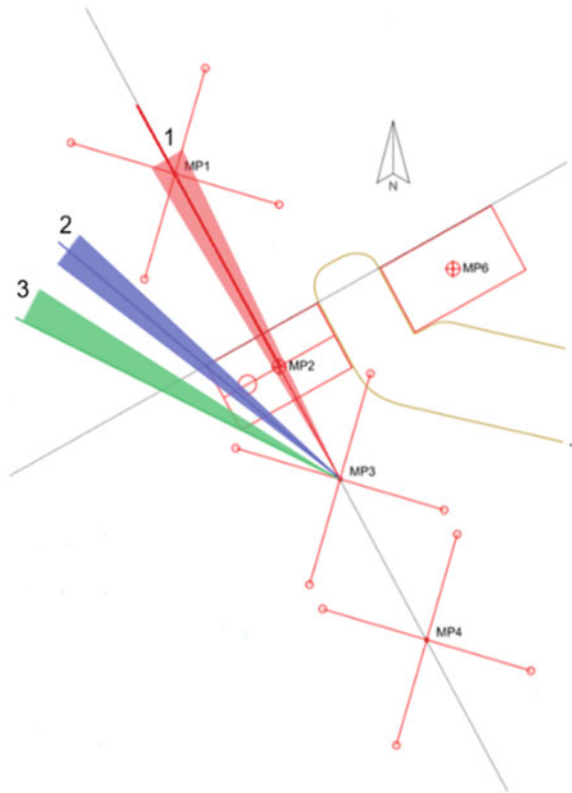
Several other properties such as temperatures, air pressure, humidity etc. are available but not considered within the performed research. Wind properties relevant for following calculations were measured with “first class adv” anemometers and “3D Ultrasonic” both produced by Adolf Thies GmbH & Co. KG.

Phase 1 measurements were taken from 07/06/2017-09/27/2017, followed by a short outage due to re-construction of the measuring set-up. Phase 2 started operating on 10/04/2017. For phase 2 only values stored before 12/10/2017 are considered for calculations in the present paper. Before starting the calculations, data sets had to be cleaned from in-complete or inaccurate measurements.

3.2 Binning

For all calculations the data is binned, both for inflow wind speed and inflow wind direction. This was done for two reasons. First, to reduce the amount of data for processing and second to evaluate representative values.

Fig. 4 Wind direction bins
(own depiction)



Three wind direction bins are defined. One represents direct inflow towards the building, one crosses the building from the North-West faced edge of the building and one just crosses the building. No change of direction is assumed for these definitions. The defined direction bins are marked in Fig. 4.

Inflow bins for both wind direction and wind speed are defined for MP1 at 7 m height. This point was chosen, because it is located in the inflow direction for the assessed wind direction and is therefore not influenced by aerodynamic effects of the building.

For all further calculations 0° is defined as North. The direction bins are defined as follows:

1. 90° related to container's front edge (direct inflow): $332 \pm 5^\circ$
2. 30° related to container's front edge: $311^\circ \pm 5^\circ$
3. 21° related to container's front edge: $301 \pm 5^\circ$

It is assumed that results are symmetric toward the connection line of MP1–MP4, thus only three wind direction bins are considered. Those were chosen from North-West direction, because most data are available from this main wind direction. No bins

from Southern direction are considered, due to the fact that only one 3D anemometer is installed at MP1 and thus no relevant results can be expected.

Wind speeds are binned as follows:

1. 2 ± 0.3 m/s
2. 4 ± 0.3 m/s
3. 6 ± 0.45 m/s
4. 8 ± 0.6 m/s
5. 10 ± 0.8 m/s
6. 14 ± 1.5 m/s

Wind speed bins are defined that way to cover the typical range of operation of small wind turbines. With increasing wind speed less values are available. Therefore, with higher wind speeds the range of fluctuation increases to allow a similar number of measurements per bin.

4 Results

Five different wind parameters have been assessed.

- Horizontal wind speed
- Vertical wind speed
- Horizontal turbulence intensity
- Vertical turbulence intensity
- Wind direction scatter

In accordance to the research on average determination for wind data in [5], all one-minute averages of wind speeds and direction scatter properties are used directly, while for turbulence intensities ten-minute averages are used.

One-minute mean values turned out not to be of sufficient fineness to deliver feasible results and are thus not discussed within this paper.

4.1 Horizontal Wind Speeds

This property is considered the most important in terms of wind turbine technology, because most installed turbines can only convert horizontal inflow. Additionally, the wind-power is dependent on the third power of the windspeed, as shown in the following Eq. (1).

$$P_w = \frac{1}{2} \rho v^3 A \quad (1)$$

Table 2 Number of available values for horizontal and vertical wind speed measurements

Number of measurements	2 m/s	4 m/s	6 m/s	8 m/s	10 m/s	14 m/s
Direction 1—phase 1	395	1118	1923	1151	550	18
Direction 1—phase 2	193	404	683	811	584	69
Direction 2—phase 1	310	960	759	307	73	0
Direction 2—phase 2	184	313	439	315	155	23
Direction 3—phase 1	310	541	348	193	85	2
Direction 3—phase 2	169	272	336	242	104	8

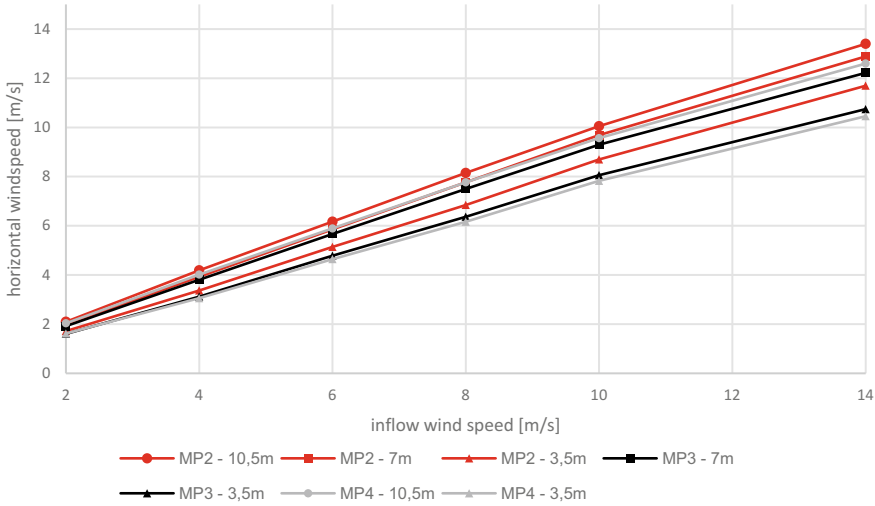


Fig. 5 Horizontal windspeed, phase 1, direction 1 (own depiction)

Table 2 shows the number of measurements for every bin area that is available for horizontal wind speed measurements. The same amount of values also applies to vertical wind speed measurements in Sect. 4.2.

Horizontal wind speeds direction 1. In Figs. 5 and 6 horizontal wind speeds for phase 1 and 2 for direction 1 are displayed.

In phase 2 an almost linear relation between inflow windspeed and measured wind speeds can be identified. Lower wind speeds for measurements in lower heights are noticeable, which can be explained by friction above ground.

In phase 2 all measurements at MP2 exhibit an increase in speed, which is justified by the continuity Eq. (2).

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{v}) = 0 \tag{2}$$

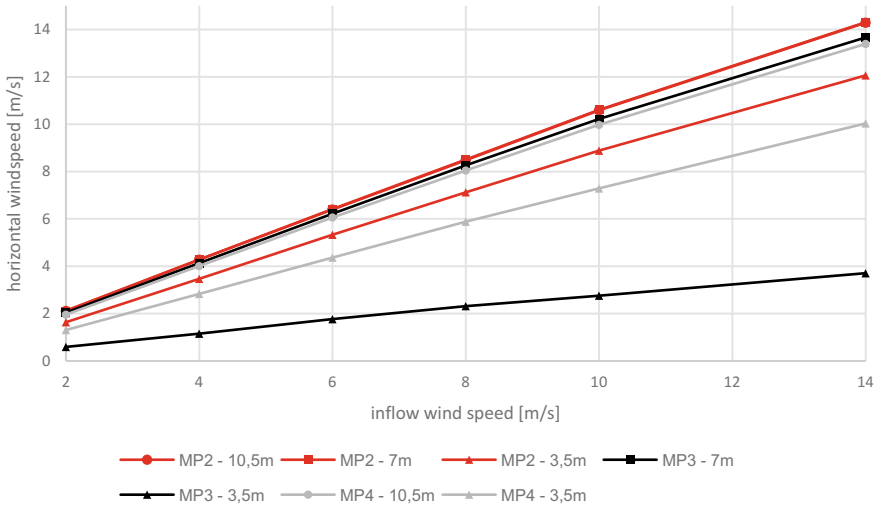


Fig. 6 Horizontal windspeed, phase 2, direction 1 (own depiction)

This effect can only be compared directly at 7 m height, as for both phases the measurements are taken at 7 m. At this height an increase of approx. 10% is investigated.

MP3 has a slight increase in windspeed at 7 m, while at 3.5 m a clear decrease is given. This anemometer is in the wake zone behind the building.

MP4 exhibits a slight decrease of wind speed at 3.5 m and a slight increase at 10.5 m. At a distance of 15 m, which equals approx. five times the height of the building, the impact of the obstacle is almost not distinguishable. This meets the findings of *The fence experiment – full-scale lidar-based shelter observations* [6] performed by DTU in 2016.

Horizontal wind speeds direction 2. In Fig. 7 horizontal wind speeds for phase 2 for direction 2 are displayed.

For measurements in phase 1 no different behavior compared to direction 1 can be observed.

In phase 2 at MP2 only at 7 m height a difference is investigated compared to direction 1. The impact of the obstacle at that height is stronger than for direction 1.

At MP3 at 7 m height no difference is given, but the decrease of wind speed at 3.5 m is approx. 30% less.

MP4 does not exhibit changes compared to direction 1.

Horizontal wind speeds direction 3. In Fig. 8 horizontal wind speeds for phase 2 in direction 3 are displayed. Again, no significantly different behavior for phase 1 can be observed compared to direction 1, hence it is not depicted herein.

The effects in direction 3 are no different from the other two directions. Only, the effects are not as strong as for directions 1 and 2.

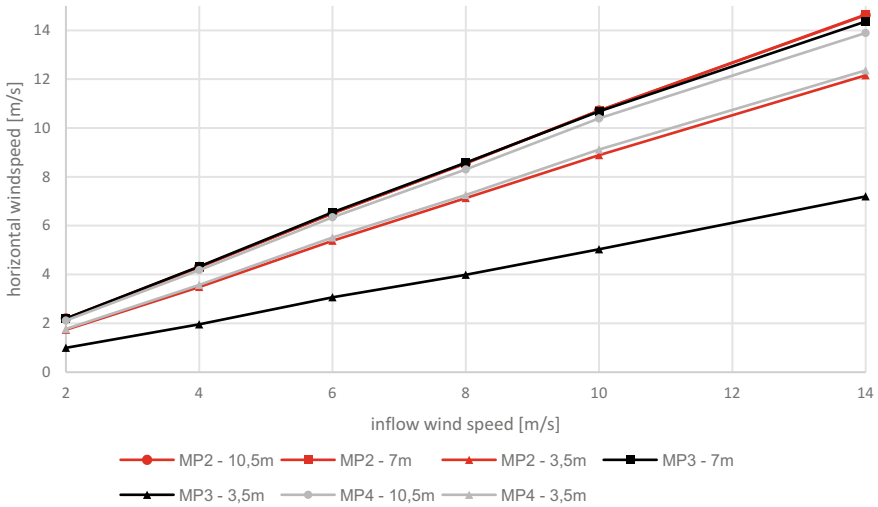


Fig. 7 Horizontal windspeed, phase 2, direction 2 (own depiction)

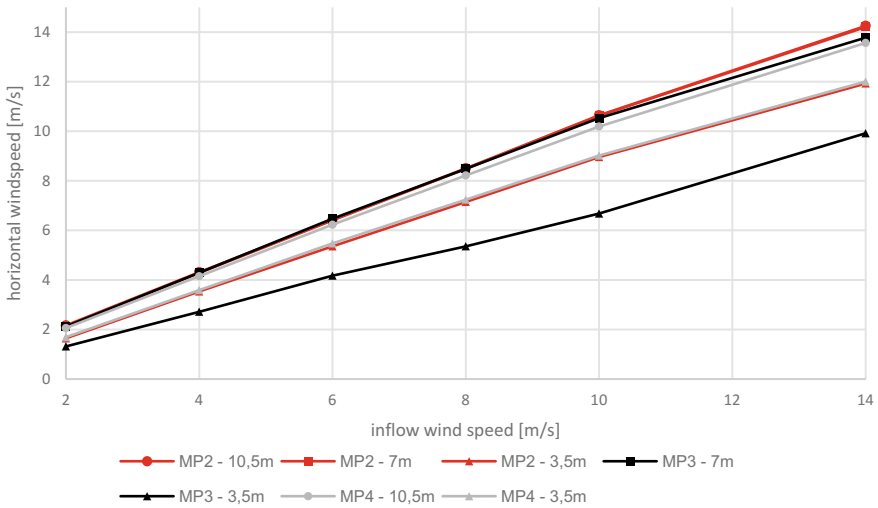


Fig. 8 Horizontal windspeed, phase 2, direction 3 (own depiction)

4.2 Vertical Wind Speeds

Vertical windspeeds are processed in order to gain an impression of how wind gets deviated from its' original flow. In regards of wind energy production, this vertical component generally means loss of potentially usable power as turbines can mostly not harvest vertical wind speeds.

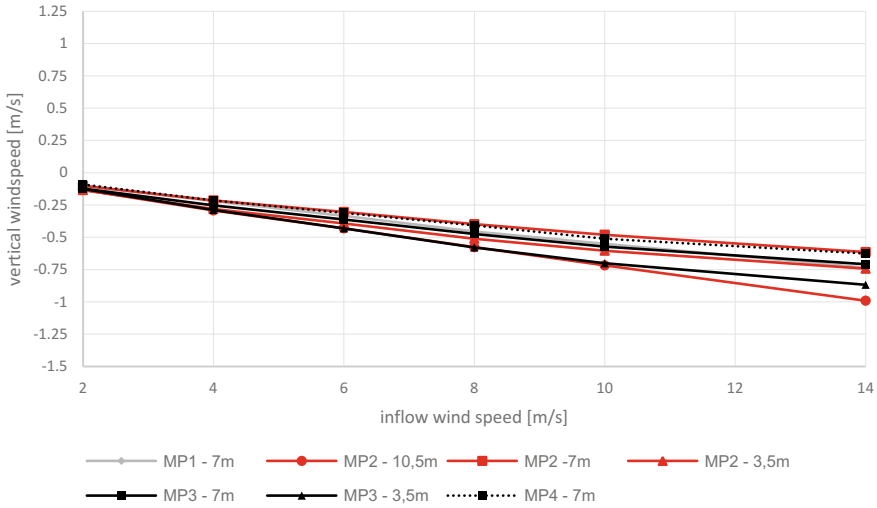


Fig. 9 Vertical windspeed, phase 1, direction 1 (own depiction)

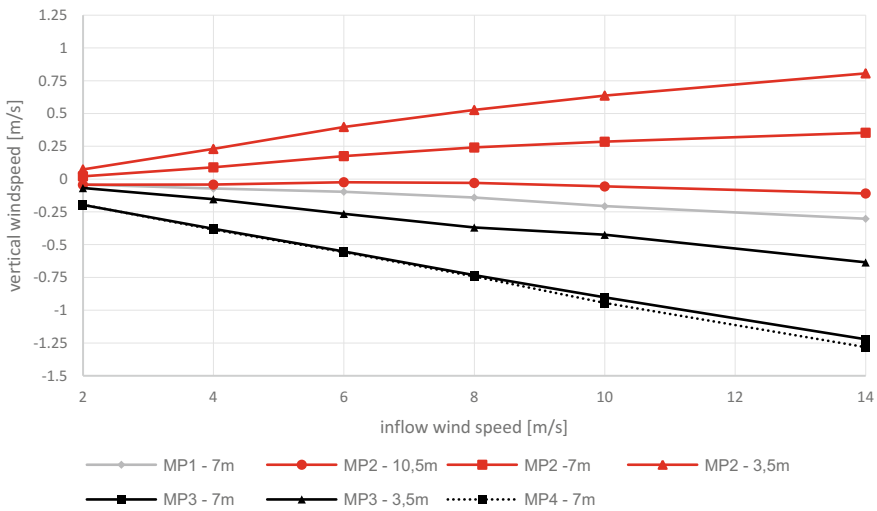


Fig. 10 Vertical windspeed, phase 2, direction 1 (own depiction)

It stands out that for all wind speeds the vertical wind speed component in phase 1 is negative. It is assumed that this effect occurs due to the downward slope of the site. To support this thesis vertical windspeeds in opposite direction ($152^\circ \pm 5^\circ$) were evaluated at MP2, which leads to the expected result of solely positive vertical wind speeds.

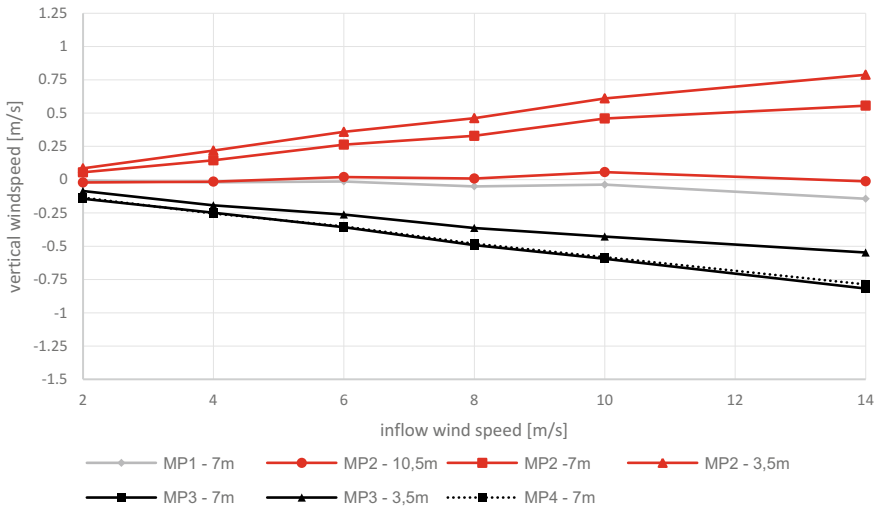


Fig. 11 Vertical windspeed, phase 2, direction 2 (own depiction)

Vertical wind speeds direction 1. In Figs. 9 and 10 vertical wind speeds for direction 1 in phase 1 are displayed. Again, on the x-axis horizontal wind speeds at MP1 in 7 m height are plotted as reference values.

Vertical wind speeds in phase 1 behave in a manner so that the wind flows parallel to the ground. This behavior is the same for all three observed directions.

Vertical wind speed measurements at MP1 at 7 m height are also included. It can be assumed that already at this distance to the obstacle an impact on the wind stream can be identified. The wind is accelerated upwards. Again, this effect can be explained with the principle of continuity. The air has to elude the building in order to avoid congestion.

At MP2 for inflow wind speeds below 3 m/s, the wind speed is accelerated in negative z-direction. Above 3 m/s this effect switches to the opposite and increases with decreasing measuring height above the building.

At MP3 an acceleration in negative z-direction is given at 7 m height while in positive z-direction at 3.5 m height. The same effect as for 7 m also occurs at MP 4 at 7 m height. The effect of acceleration in negative z-direction can be explained by the air sinking back down after the obstacle in order to reach air-pressure equalization.

The acceleration of the wind above the roof can be explained by the stream being compressed and therefore accelerated while passing over the building.

Vertical wind speeds direction 2 and 3. As for horizontal wind speeds, no different behavior for phase 2 in direction 2 or 3 for vertical wind speeds can be interpreted from the measuring results. Hence, only phase 2 results are plotted for direction 2 in Figs. 11 and 12.

For direction 2 the effects are the same as for direction 1, only slightly less distinct.

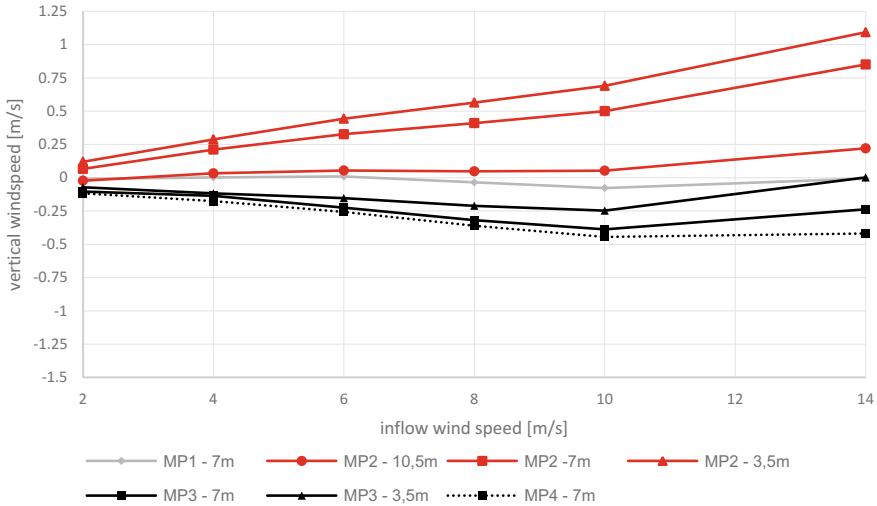


Fig. 12 Vertical windspeed, phase 2, direction 3 (own depiction)

Table 3 Number of available values for horizontal turbulence intensities

Number of measurements	2 m/s	4 m/s	6 m/s	8 m/s	10 m/s	14 m/s
Direction 1—phase 1	395	1118	1923	1151	550	18
Direction 1—phase 2	186	399	680	811	584	69
Direction 2—phase 1	310	960	759	307	73	0
Direction 2—phase 2	182	309	439	315	155	23
Direction 3—phase 1	310	541	348	193	85	2
Direction 3—phase 2	164	269	335	242	104	8

For direction 3 the accelerations in positive-z direction are stronger than in direction 1. For all other measuring points no significant difference in this situation can be identified.

4.3 Horizontal Turbulence Intensity

The horizontal turbulence is defined as usual in common literature (3).

$$Ti = \frac{\sigma}{u} \tag{3}$$

σ stands for the standard deviation, and u for the arithmetic mean over 10 min as defined in Sect. 3.1. Here the values are calculated from one-minute mean values

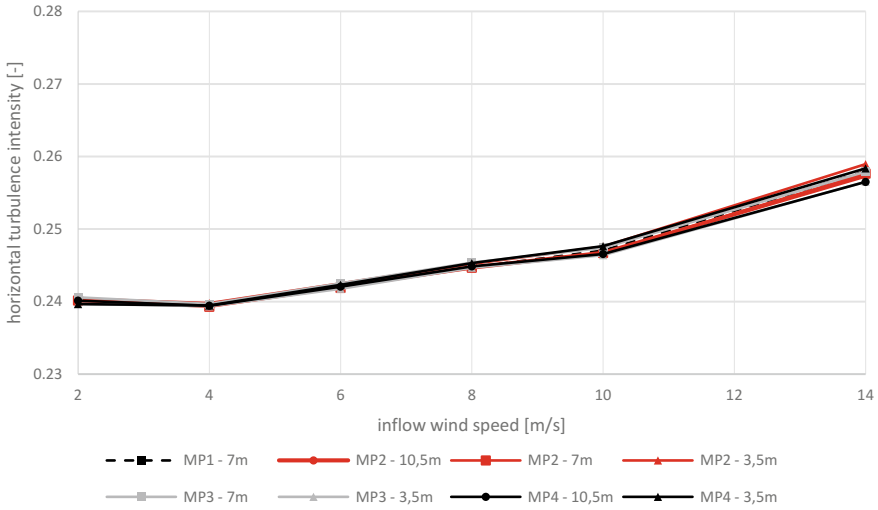


Fig. 13 Horizontal turbulence intensity, phase 1, direction 1 (own depiction)

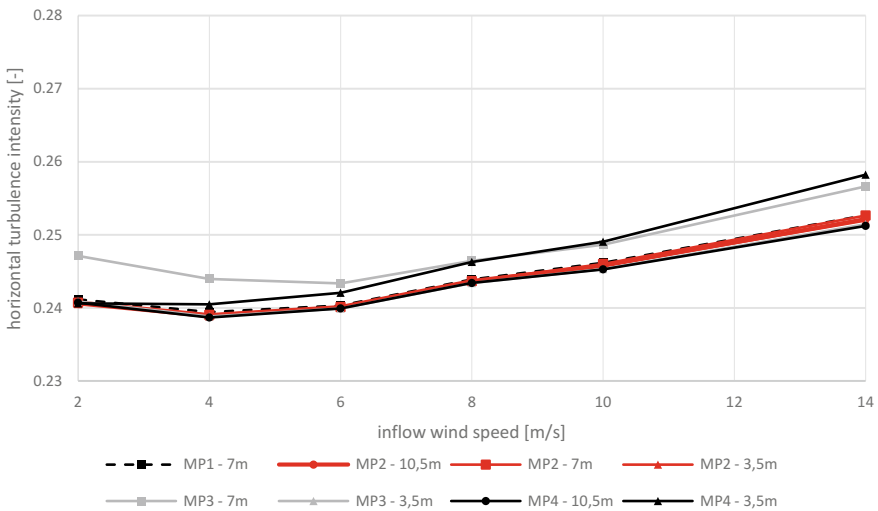


Fig. 14 Horizontal turbulence intensity, phase 2, direction 1 (own depiction)

from the data loggers and it is ignored that those already have standard deviations. The number of available datasets for processing of horizontal turbulence intensities is given in Table 3.

Horizontal turbulence intensities direction 1. In Figs. 13 and 14 the horizontal turbulence intensity for direction 1 phase 1 and 2 is displayed.

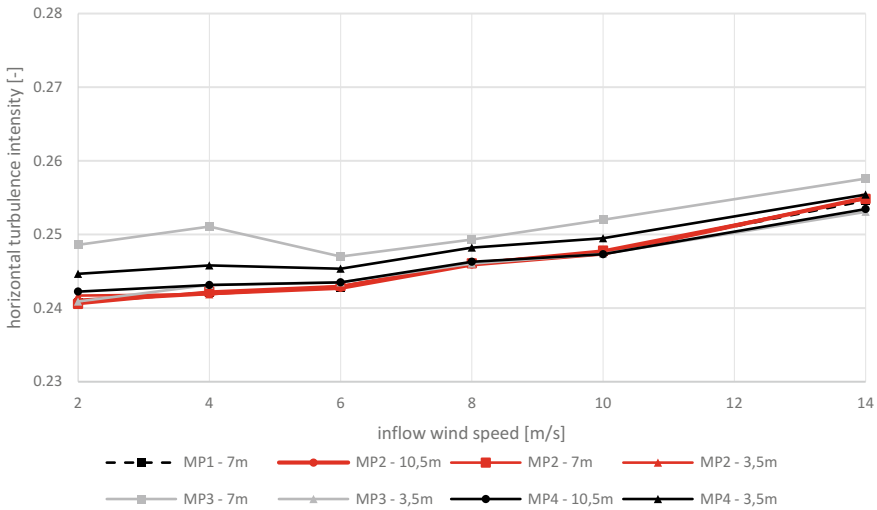


Fig. 15 Horizontal turbulence intensity, phase 2, direction 2 (own depiction)

In phase 1 with increasing inflow wind speed, the turbulence intensity increases. Additionally, no dependency on height can be interpreted for neither direction. In phase 2 for inflow wind speeds between 2 and 4 m/s horizontal turbulence intensity decreases. Above 4 m/s an increase similar to phase 1 is given. In general, horizontal turbulence intensities seem to be lower in case of obstacles in the wind stream, except for MP3 at 7 m height where at every inflow wind speed, an increase of horizontal turbulence intensity can be measured. This can be explained by the occurrence of eddies created at the edge of the building.

The impact of the building on the horizontal turbulence intensity can still be clearly measured at the highest measurements. So, the impact in vertical component of the wind is stronger than the impact on horizontal wind speeds. Also, an impact can clearly be measured at MP4 in 10.5 m height. Which means the effect of buildings on horizontal turbulence intensities is more significant than the impact on wind speeds.

Horizontal turbulence intensity direction 2 and 3. Figure 15 shows the results of turbulence intensity for direction 2 in phase 2. Phase 1 in direction 2 is no different from direction 1, phase 2.

The difference to direction 1 in phase 2 appears to be minimal, except for MP3 in 7 m height where an increase of horizontal turbulence intensity is verified especially for lower wind speeds.

Figure 16 shows results for phase 1 in direction 3.

The very different behavior in comparison to direction 1 cannot be explained within this research paper. It might be due to eddies, but this cannot be verified at this point. Only, the expected increase of horizontal turbulence intensity with increasing inflow speed can be identified.

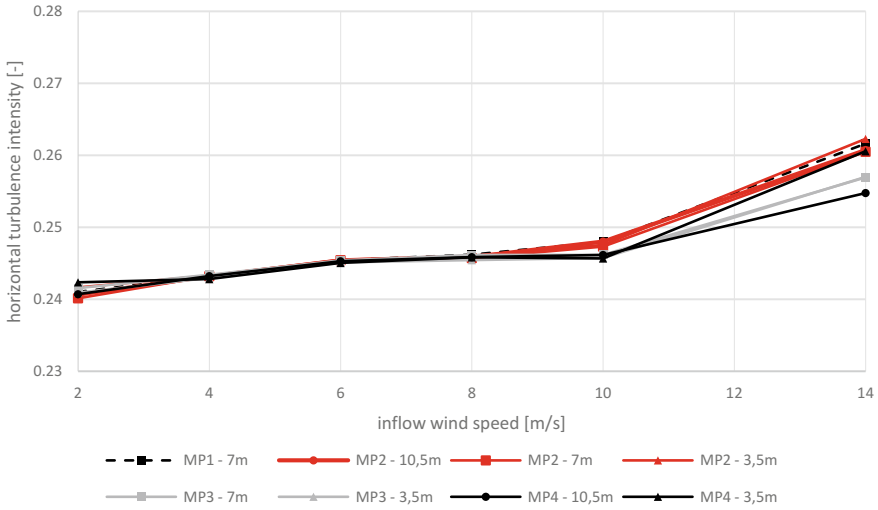


Fig. 16 Horizontal turbulence intensity, phase 1, direction 3 (own depiction)

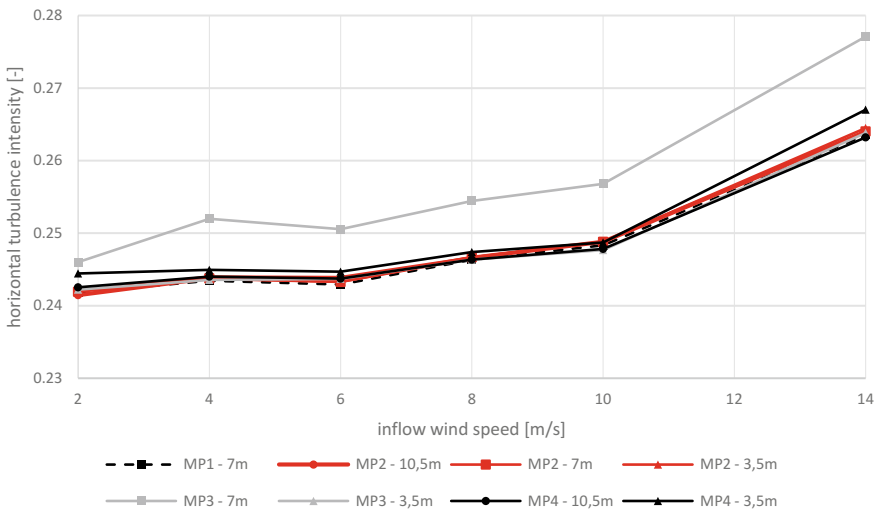


Fig. 17 Horizontal turbulence intensity, phase 2, direction 3 (own depiction)

Horizontal turbulence intensity results of direction 3 phase 2 are displayed in Fig. 17.

In comparison to direction 1, the effects are the same but less distinct, with only one exception at MP3 in 7 m height. At this point a clear increase for all wind speeds is given. Again, this effect comes from air being compressed and accelerated. The number of available datasets for processing of vertical turbulence intensities is given in Table 4.

Table 4 Number of available values for vertical turbulence intensities

Number of measurements	2 m/s	4 m/s	6 m/s	8 m/s	10 m/s	14 m/s
Direction 1—phase 1	392	1116	1922	1151	550	18
Direction 1—phase 2	188	398	674	802	580	69
Direction 2—phase 1	304	955	754	307	73	0
Direction 2—phase 2	174	307	439	312	152	23
Direction 3—phase 1	302	531	345	191	84	2
Direction 3—phase 2	159	264	332	240	104	8

4.4 Vertical Turbulence Intensity

The vertical turbulence intensity is a rather experimental property. The goal of introducing it is to gain insights on the stability of eddies caused by the influence of the building.

This property is inspired by turbulent kinetic energy [7], but rather than generating one property for all directions in space it is tried to focus on solely horizontal effects. This is done with the intention to capture effects on vertical wind speeds that are ignored with the calculation of the typical turbulence intensity. The common definition of turbulence intensity comes from large wind research which operates in heights and horizontal wind speed ranges where vertical effects can for the better part be ignored.

Vertical turbulence intensity herein is defined in the same way as horizontal turbulence intensity defined in Sect. 4.3, with the only difference that vertical wind speeds and standard deviations are used.

In Fig. 18 phase 1 and direction 1 for turbulence intensity are plotted.

In contrast to the horizontal turbulence intensity in phase 1, vertical turbulence intensity decreases with increasing inflow wind speed. This effect is given for all measurements and directions. In absolute values vertical turbulence intensity is clearly higher than the horizontal, even exceeding 1 at times. This effect comes from the fact that values are spread positive and negative around 0 while standard deviations are per definition solely positive.

In Fig. 19 vertical turbulence intensity for direction 1 during phase 2 is displayed.

It can be said that for all directions in phase 2 for the lowest measurement at MP2, the vertical turbulence intensity is clearly lower.

Apart from that, no pattern or tendencies can be interpreted from vertical turbulence intensity plots. All plots seem to be rather chaotic and randomly spread against inflow wind speed. Vertical turbulence intensity with this kind of definition or data, turn out not to be meaningful for wind conditions above flat roof buildings.

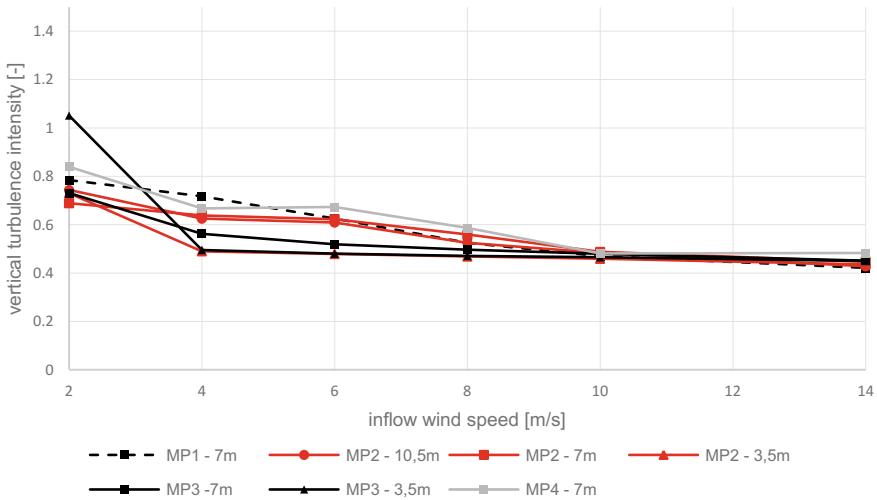


Fig. 18 Vertical turbulence intensity, phase 1, direction 1 (own depiction)

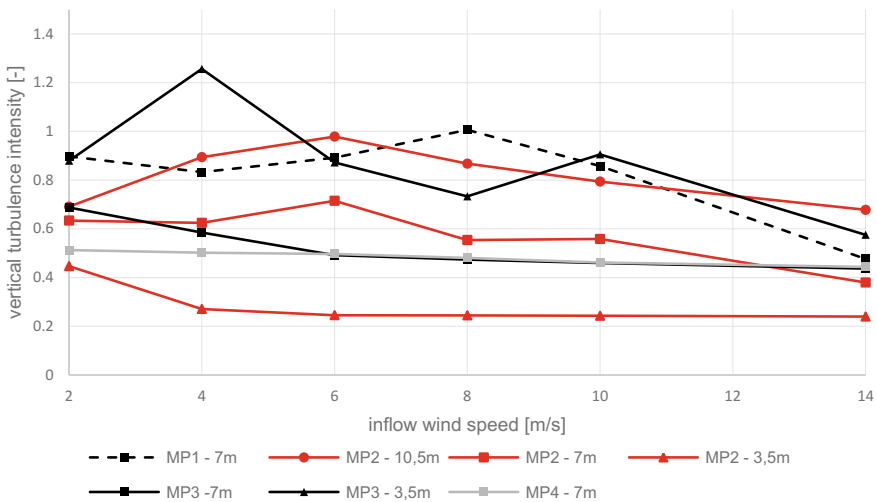
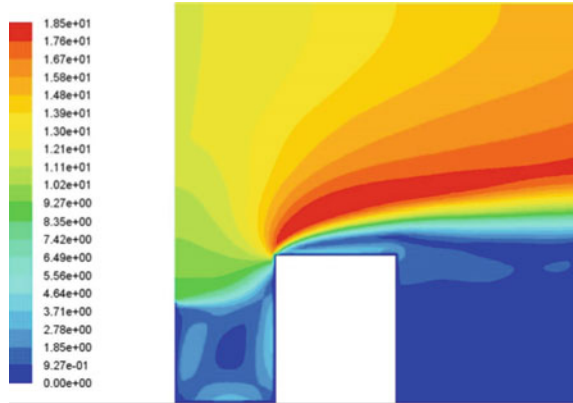


Fig. 19 Vertical turbulence intensity, phase 2, direction 1 (own depiction)

5 Conclusion

All results have been compared to the simulation results of the paper *Two-Dimensional Model of Wind Flow on Buildings to Optimize the Implementation of Mini Wind Turbines in Urban Spaces* [8] and mostly meet with their findings. This applies especially in direction 1 which is the direction in which the simulations were performed.

Fig. 20 Wind speed simulation over flat roof [8]



For all measurements it is found that wind speed increases above the building, as depicted in Fig. 20. This increase also causes a change of direction, which on the other hand leads to an increase of vertical wind speed.

In contrast to horizontal wind speed which increases almost linear with increasing inflow wind speed, vertical wind speeds show a saturating behavior. This leads to the assumption that air layers with same velocities get vertically packed tighter. This causes a higher wind speed gradient orthogonal to wind speed direction with higher wind speeds.

The results also cover with the findings in *The fence experiment—full-scale lidar-based shelter observations* [6], especially the decreasing effect of inflow other than straight.

Concluding from all reliably results (horizontal wind speed, vertical wind speed and horizontal wind speed), an installation of small wind turbines is on flat roof tops of single building is advisable in terms of wind resource. The reasons for that are an increase of power output due to higher horizontal wind speeds and less stress on the machines due to lower turbulence intensities. For free standing, a sufficient hub height and distances to the obstacle have to be respected to avoid shadow zones or highly turbulent areas.

It needs to be respected that all research was performed for one specific building far from any urban surroundings with undisturbed inflow. More research needs to be done to verify obtained results and especially improve the work on vertical turbulence intensity.

References

1. United Nations (2015) Paris Agreement. Paris, United Nations
2. Matlab R2017b (n.d.) Matlab R2017b. The MathWorks, Inc

3. Energiewerkstatt – Technisches Büro zur Förderung erneuerbarer Energie: Lageplan Energieforschungspark Lichtenegg. Friedburg (2017)
4. Tiefgraber, I.C.: Aufbauprotokoll Windmessung SmallWindPower@Home. Friedburg (2017)
5. Elliot D, Infield D (2012) An assessment of the impact of reduced averaging time on small wind turbine power curves, energy capture predictions and turbulence intensity measurements. Wiley Online Library, Glasgow
6. Peña A, Bechman A, Conti D, Angelou N (2016) The fence experiment—full-scale lidar-based shelter observations. Wind Energy Science Discussion, Roskilde
7. Šavli M (2012) Turbulence kinetic energy—TKE. University of Ljubljana, Ljubljana
8. Sáenz-Díez Muro JC, Jiménez EM, Blanco JMB, de la Parte MP, Blanco JF (2010) Two-dimensional model of wind flow on buildings to optimize the implementation of mini wind turbines in urban spaces. University of La Rioja, Logroño