Matthias Haase • Kristian Skeie • Tron Vedul Tronstad

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RESEARCH 19

Building integrated vertical wind turbines

EXPERIENCES FROM THE ROOF OF BISKOP GUNNERUS GATE 14 IN OSLO

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Abstract

The intention of this project was to test vertical axis wind turbines in the built environment. There seemed to be a lack of knowledge necessary to integrate micro wind turbines on buildings. Therefore, Entra took the initiative to install wind turbines and measurement devices and test the turbines on an actual building under real weather conditions.

This report describes results of the installation of vertical axis wind turbines on the roof top of Biskop Gunnerus gate 14 in Oslo. Measurements of wind, electricity production and noise were taken and correlated. The results show a good match. Technical challenges during the project are described and the advantages and disadvantages of the wind turbines are discussed. The conclusions highlight the need for further work in order to harvest the potential of wind power integrated into the built environment.

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APPENDIXES

A – Wind and power measurements

B – Wind turbines installation and power curves

C – Strategy

D – Wind power theory

E – Noise report (in Norwegian)

1 Background

By generating electricity on site, wind turbines avoid transmission losses and the costs of a separate connection to the local distribution network. They also provide a visual statement and highlight a commitment to sustainable energy by promoting a «green» image (Cace, et al., 2007). These qualities have spurred increasing interest and support for small scale wind technologies from politicians, industry, local authorities and the general public. The development of building integrated wind turbines has taken place despite the notion that the wind velocity generally will be less, the turbulence and wind shear greater, and the local flow effects will be more specific than in an adjacent comparable rural area. Urban wind applications include all kinds of small wind installations in urban or built environment, presenting a relatively new application for small wind turbines. Associated technologies are still being developed and entering the Norwegian market (Blanch, 2002).

1.1 Intentions

In Norway, the interest in wind generation is extensive, but mostly focused on large scale wind farms. Up to now there have been no guidelines, regulations or specific information about urban wind generation. The intention of this project was to test vertical axis wind turbines in the built environment. There seemed to be a lack of knowledge necessary to integrate micro wind turbines on buildings. Therefore, Entra took the initiative to install wind turbines and measurement devices and test the turbines on an actual building under real weather conditions. SINTEF Building and Infrastructure was engaged to make measurements and analyse the results. This report summarizes the results of these measurements and provides some general conclusions.

1.2 The building

It was decided to use the roof of the Biskop Gunnerus gate 14 tower building in Oslo for the installation, formerly known as Postgirobygget (The Post tower building). The building is the highest in Oslo, it is 111 m high and consists of two parts, one with 23 and one with 26 floors. The building was designed by Norwegian architect Rolf Christian Krognes and, constructed in 1975 and has 51.000 m^2 (net floor area.). In 2003, the building underwent a renovation in which seven floors were added and the building was split in to two towers. Parts of the building serve as the home office to Posten Norge, the Norwegian postal service. After the renovation, Aftenposten newspaper moved into the building. Biskop Gunnerus gate 14 is owned by Entra Eiendom. Entra Eiendom AS is a Norwegian property company owned by the Norwegian Government through the Ministry of Trade and Industry. (http://www.entra.no/en/)

Figure 1: Plan view of Biskop Gunnerus gate 14 building with roof area (www.google.com/maps)

*Figure 2: Side view of post tower building (*en.wikipedia.org/wiki/**Postgirobygget**_(building))

1.3 Wind power theory

In order to be able to evaluate wind turbines it is important to review aerodynamic physics of wind turbines. The equations are taken from various sources (compare Hau, 2000; Kaltschmitt, Streicher and Wiese, 2006; Dutton and Blanch, 2005; Mertens, 2006). Wind turbines aim to convert the power of the wind into electricity. To estimate energy production some physical laws are reviewed below.

The power law shows the correlation between the theoretical power in the wind, dependent on wind velocity, rotor area and density of air.

Power law:

$$\boldsymbol{P_{wind} = \frac{1}{2} \times v^3 \times \rho \times A} \qquad \textbf{(eq. 1)}$$

with
ρ = density [kg/m^3]
A = area (rotor cover)
v = wind velocity [m/s]

The decisive factor is the wind velocity with third power flowing into this formula. A doubling of wind velocity results in an eightfold performance increase, and vice versa. If the actual wind velocity at a site is 10% less than predicted, the performance is reduced by 27%.

Another important physical law is the wind shear power law which gives the correlation between the height of the wind turbine, the wind velocity and the terrain of the surroundings.

Wind shear power law:

$$\boldsymbol{v_{calc1} = v_{station} \times c \times \left(\frac{h_{roof}}{h_{station}}\right)^{\alpha}} \qquad \textbf{(eq. 2)}$$

with

v_{calc1} = wind velocity on roof
$v_{station}$ = wind velocity at weather station
c = terrain factor
α = wind shear factor
h_{roof} = height of roof
$h_{station}$ = height of wind measurement device at weather station

Table D.1 in appendix D shows the correlation between the terrain factor and the wind shear factor for different surrounding settings.

The deciding size which determines how much electricity can be produced by the wind turbine is the power coefficient. The theoretical power of the wind is multiplied by the number of hours per year and the power coefficient which results in the annual theoretical electricity production.

Power coefficient:

$$\boldsymbol{E_{el} = P_{wind} \times c_p \times 8760h} \qquad \textbf{(eq. 3)}$$

with

E_{el} = electricity production [kWh]
P_{wind} = power of wind
c_p = power coefficient

The power coefficient indicates which part of the kinetic energy in the wind is used by a wind turbine. A 100% removal of the kinetic energy is not possible. The theoretically calculated maximum for free flow around the rotors is 59.3%, but different types of rotors provide different coefficients depending on their tip-speed-ratio (TSR). TSR for wind turbines is the ratio between the rotational velocity of the tip of a blade and the actual velocity of the wind, v.

$$\boldsymbol{TSR = \frac{\omega \times R}{v}} \qquad \textbf{(eq. 4)}$$

with

ω = rotor rotational velocity in radians/s
R = rotor radius in m
v = wind velocity in m/s

TSR is related to efficiency, with the optimum varying with blade design (Hau, 2000). Higher tip velocities result in higher noise levels and require stronger blades due to large centrifugal forces.

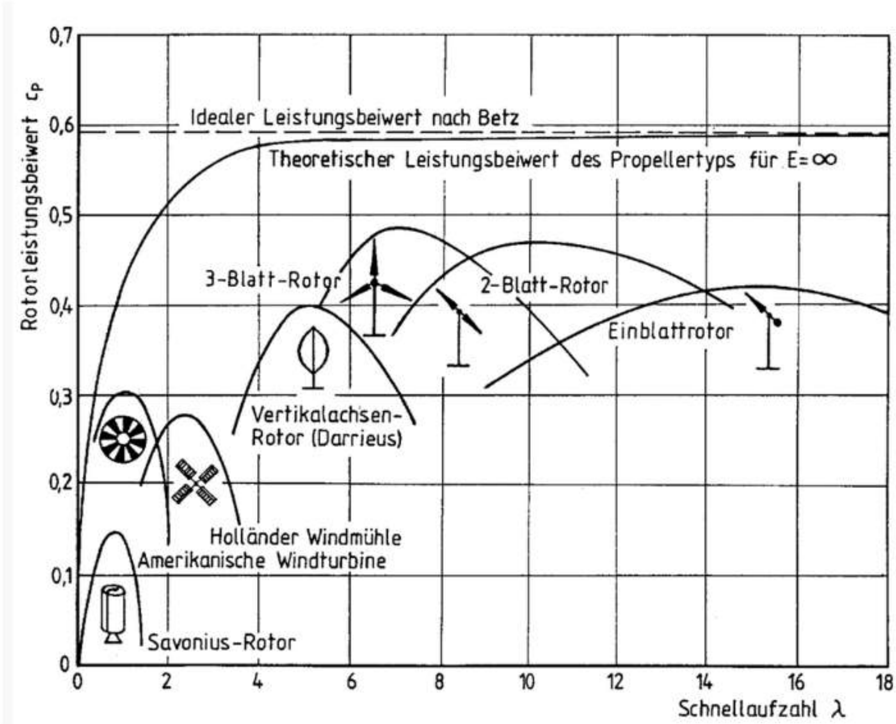

Figure 3: Power coefficients of different rotor types in relation to TSR (λ) (Hau, 2000)

In practice, wind turbines with vertical axis that use the drag principle (Savonius-Rotor) will have power coefficients between around 11–14% (Mertens, 2006).

In order to evaluate wind turbines it is useful to compare the theoretical electricity production to the measured electricity production. This can be expressed in a power coefficient, c_p, which takes into account all mismatches between theoretical and measured values. It includes the efficiency factor of the converter as well as hours when there was wind but the wind turbine did not produce electricity, etc.

The wind velocity and wind direction on top of the building together with the electricity production of the two rows of installed wind turbines was monitored. In addition, corresponding wind values from two weather measurement stations in Oslo (Alna and Blindern) as well as averaged historical data were collected. With these data sets it was possible to make comparisons between the particular measurements and to develop correlations between weather stations and rooftop. The intention was to derive a clearer understanding of how and where to measure wind velocity and direction on roofs in the built environment.

Especially interesting is the correlation between wind velocities and direction between measurements on the top of the building and at weather stations nearby (Alna and Blindern). Therefore, the wind velocity and direction measurements were compared using the following formula:

$$v_{calc,i} = v_{station,i} \times c_i \times \left(\frac{h_{roof}}{h_{station}}\right)^{\alpha} \qquad \textbf{(eq. 5)}$$

with

$v_{station,\,i}$ = wind velocity at weather station (hourly data), index 1 and 3 for Alna, index 2 and 4 for Blindern
$h_{station}$ = height of weather station = 10 m
h_{roof} = height of installed wind turbines = 89 m
$c_{1,2}$ = 0.35/0.21 ratio of terrain factors (from Table D.1)

$c_{3,4}$ = 1, assuming the same terrain between the weather stations and Biskop Gunnerus gate 14
α = 0.33 (from Table D.1, City terrain)

The results were compared with each other ($v_{calc,1}$, $v_{calc,2}$, $v_{calc,3}$, $v_{calc,4}$, v_{mea}) and are presented in section 3.1.

Based on calculated wind velocities it was possible to simulate theoretical wind power.

$$\boldsymbol{P_{theo,i} = \frac{1}{2} \times v_{calc,i}^3 \times \rho \times A} \qquad \textbf{(eq. 6)}$$

with
A = rotor area = 7.84 m^2 (effective), here calculated with rotor unit area = 0.98 m^2 (effective) and 8 units
ρ = density of air (assumed to be constant) = 1.25 kg/m^3 . Air density was kept constant even though it depends on height as well as temperature, see appendix A figure A.7.
$v_{calc,i}$= calculated wind velocity (from eq. 6)

The results were compared with each other (P_{roof} , $P_{theo,m}$, $P_{theo,1}$, $P_{theo,2}$, $P_{theo,3}$, $P_{theo,4}$) and are presented in section 3.2.

Energy production based on measured wind velocity on the rooftop can be calculated with:

$$\boldsymbol{E_{theo,m} = \int_1^n P_{theo,m} \times \Delta t} \qquad \textbf{(eq. 7)}$$

with
$P_{theo,i}$ = theoretical wind power (from eq. 6)
Δt = various periods

The measurement results for wind velocity and power were compared and used to calculate the power coefficient.

$$\boldsymbol{c_p = \frac{P_{mea}}{P_{theo,m}}} \qquad \textbf{(eq. 8)}$$

with
P_{mea} = measured power output
$P_{theo,m}$ = theoretical electric power with measured wind velocity (from eq. 8)

Thus it was possible to simulate the electricity production for the various measured wind velocities:

$$\boldsymbol{E_{calc,i} = c_p \times E_{theo,i}} \qquad \textbf{(eq. 9)}$$

With
c_p = power coefficient from (eq.8)
$E_{theo,i}$ = theoretical electricity production (from eq. 7)

Results are presented in section 3.2.

2 Installations

The wind turbines were installed in two rows on the flat roof. Four units were placed in each row. Each unit consisted of three vertical axis rotor blades. The dimensions of the installation are given in table 1.

Table 1: Dimensions of installations

	Width	Height	Area
Rotor blades	0.33 m	1.1 m	0.373 m^2
Unit	1.3 m	1.3 m	1.69 m^2 (0.98 m^2 eff.)
Rows	5.2 m	1.3 m	6.76 m^2 (4.8 m^2 eff.)
System	2 x 5.2 m	1.3 m	13.52 m^2 (9.6 m^2 eff.)

2.1 Wind turbines

The wind turbines in this project were vertical axis wind turbines of the type Turbomill^{TM} by Windstream inc, USA. Figure 5 gives form and dimensions of one unit with three rotor blades mounted together on a rack. The racks with units were mounted on a steel construction which was put on top of the roof on 10 cm thick insulation mats for weight distribution. Vibration issues were not evaluated. Noise transmission down into the building (as a result of vibration and noise production from wind turbines) was also considered not important and therefore was not evaluated.

Figure 4: Installation of wind turbines and wind measurement devices (PHOTO: SINTEF Byggforsk)

Figure 5: Wind turbines unit with dimensions, 1.3m x 1.3m x 0.64m; 0.98m^2 effective area; taken from data sheet from producer. See also appendix B.

Figure 6 shows the power curve of the Turbomill ™ provided by Windstream inc. The graph shows the motor measurement output rate from the converter (W) in correlation to the wind velocity. It illustrates that from wind velocities of 3 m/s there is continuously increasing power output until 17 m/s, when the wind turbines stop producing electricity. At wind velocities of 17 m/s an output rate of 500 W can be expected, but the output rate drops to 143 W at 11 m/s and further down to 10 W at 4 m/s. This illustrates that the power output depends to a high degree on the wind velocity. Thus wind velocity and wind direction next to the installed wind turbines were measured.

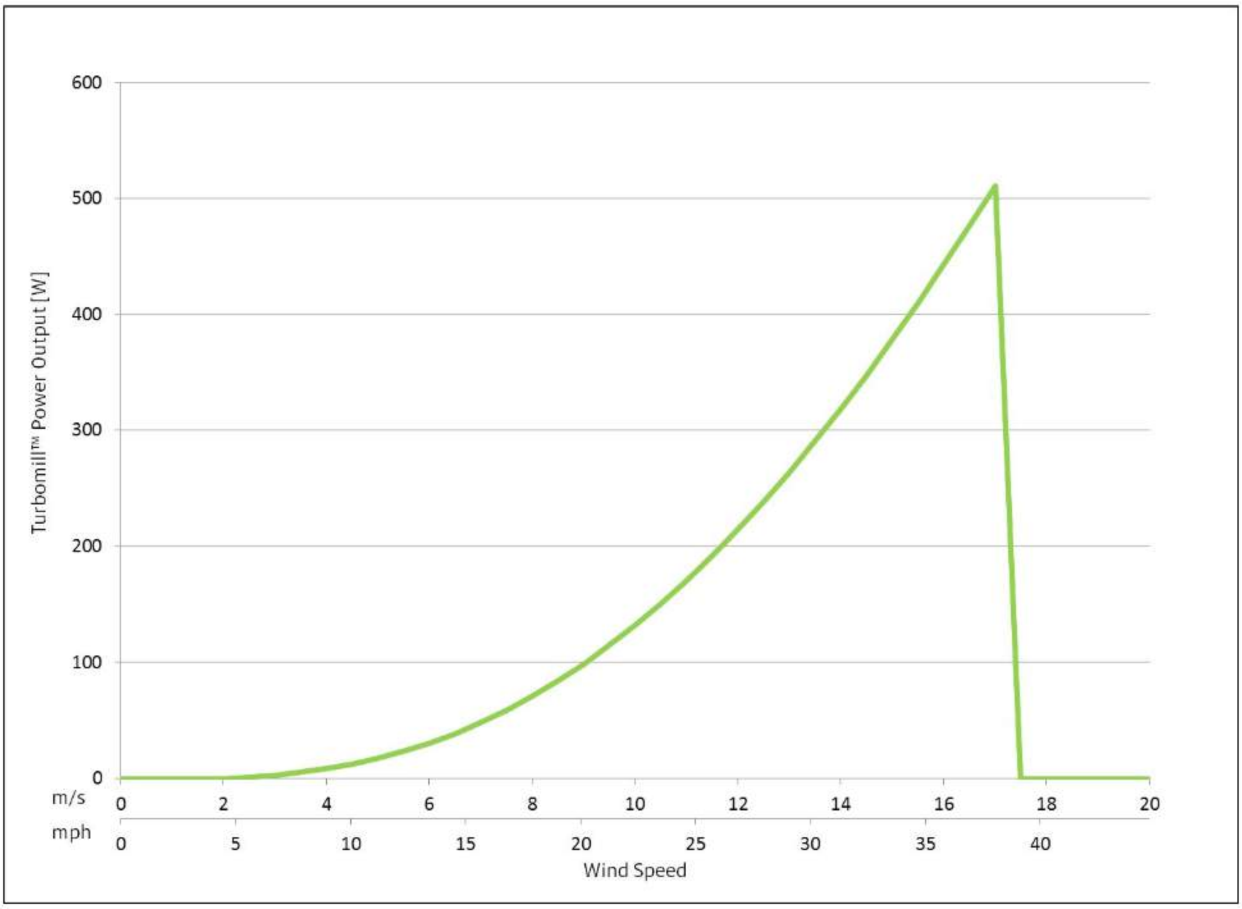

Figure 6: Product power curve of one wind mill unit from Turbomill, taken from data sheet from producer. See also appendix B.

2.2 Measurement devices

Different measurement devices were used for measuring wind velocity, wind direction, power output and vibration in 5 minute intervals. Since vibration was not considered, the vibration measurements were not calibrated. The results were collected by a data logger on the roof and periodically tracked out on a computer. A web-based software that works with the HOBO Remote Monitoring System was used to collect the measured data (HOBO).

Figure 7 shows the measurement device installed next to the North facing row of wind turbines. Figure 8 shows one of the battery packs and the thermal resistance installed in the technical room.

The schematic representation of the whole measurement setup is shown in Appendix A.

Wind data was also collected from two weather stations nearby. One weather station is located at the Meteorological Institute (met) in Blindern, the other at Alna. Figure 9 shows the location and surroundings of the stations. More information about the weather stations can be found in Appendix A.

Figure 7: Wind measurement devices (PHOTO: SINTEF Byggforsk)

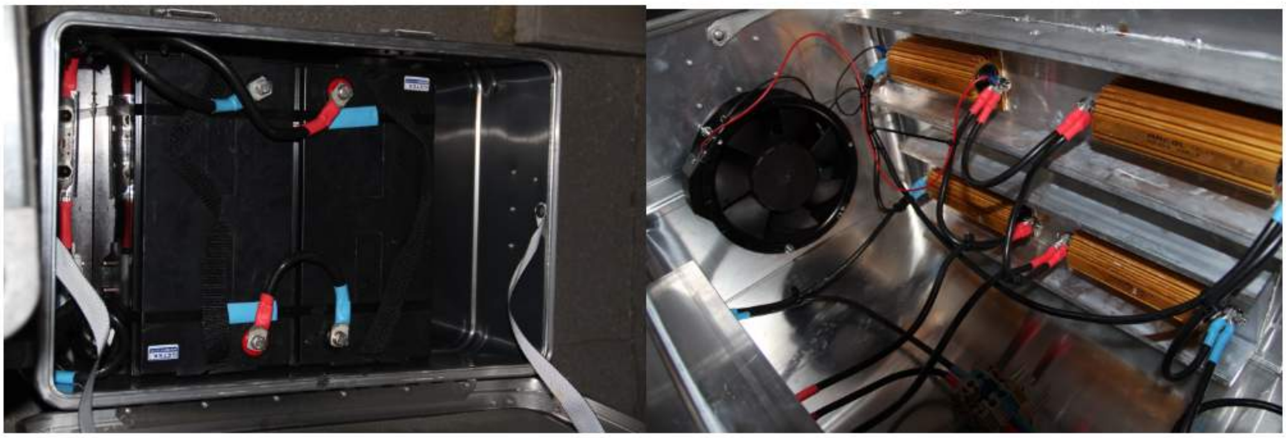

Figure 8: Battery pack (left) and thermal resistance device (right) (PHOTO: SINTEF Byggforsk)

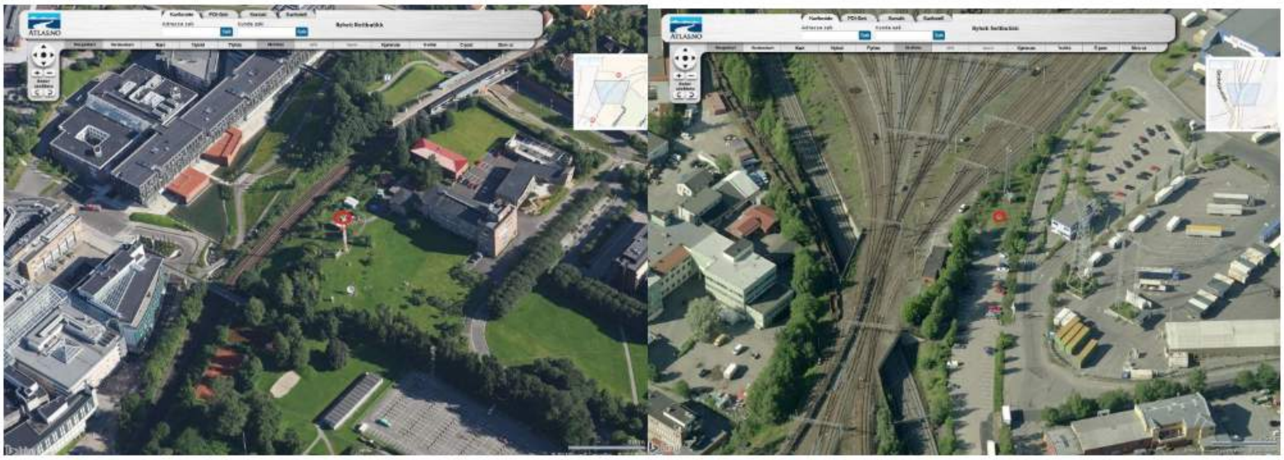

Figure 9: Location of weather stations Blindern (left) and Alna (right) (www.atlas.no)

2.3 Noise measurement procedure

Because the noise from a wind turbine increases with wind velocity, it was important to measure the noise in strong winds. Two possible solutions were proposed for measuring the wind turbine unit; either it could be measured in a wind tunnel, or outside in natural wind. Since there are no silent wind tunnels in Norway, the latter solution was selected. To reduce the background noise level a desolated place near the top of Gråkallen, a small mountain outside Trondheim, Norway, was selected as the location for the measuring. The surroundings had little vegetation that could influence the background noise level as the wind increased.

The noise from the wind turbine unit was measured during week 41 and 42 in 2012. Measurements were performed according to the NORDTEST sphere method (NORDTEST, 1991). This method uses four microphone positions to calculate the radiated sound power from a source. In Figure 10 the measurement setup can be seen.

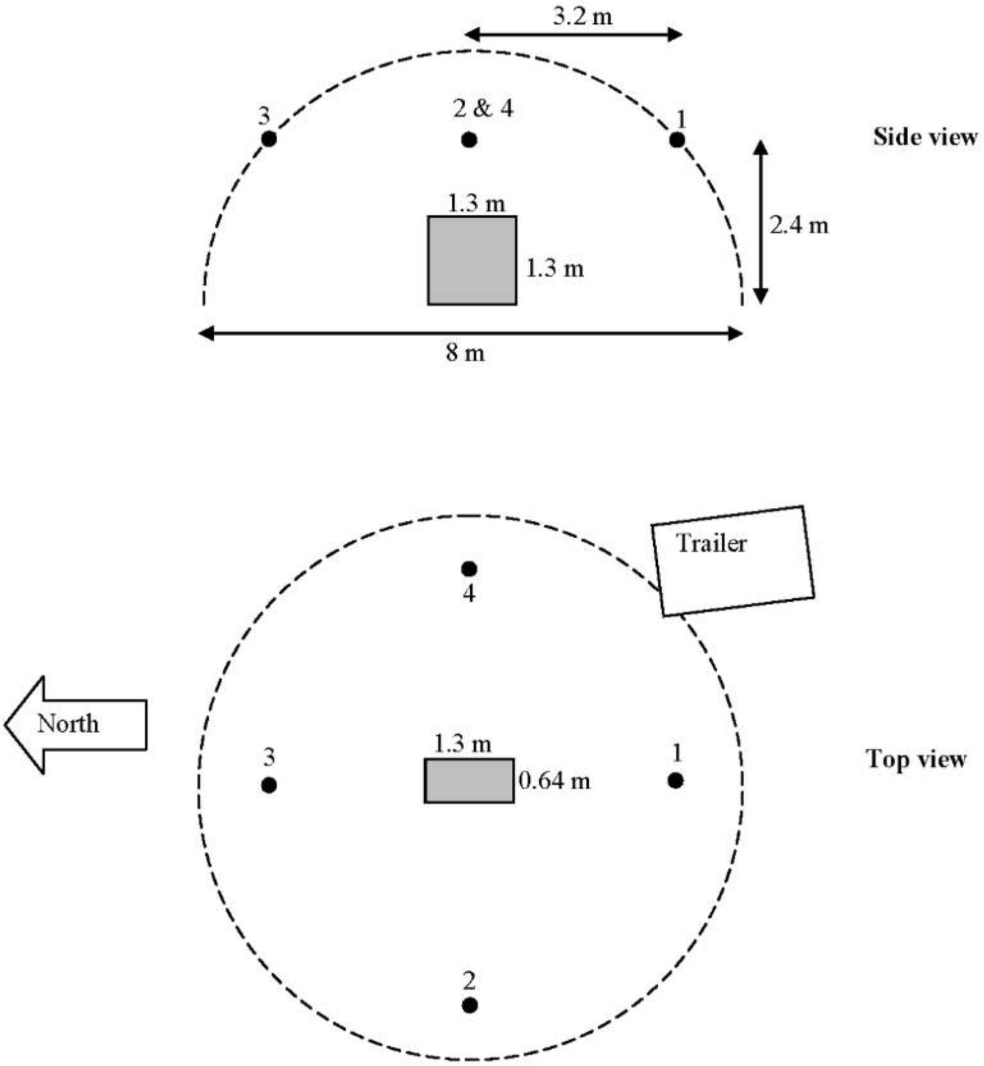

Figure 10: Noise measurement setup. The gray box in the middle is the wind turbine unit. The black dots are the microphones, and the trailer is where the noise logging units, and the weather station with logging pc were stored. The dashed line is the virtual sphere used to calculate the radiated noise.

The noise was measured using four Norsonic ½" microphones connected to two Norsonic Nor121 noise logging units. Each microphone was fitted with a 90 mm wind shield. In addition the wind velocity and direction was measured using a Vaisala WXT520 weather station connected to a computer. Both the noise and the weather measurements used 1 minute intervals in the data logging.

Background noise measurements were performed at the end of the measuring period without the wind turbine unit present.

3 Measurement results

The measurement campaign for the wind turbines located at the top of Biskop Gunnerus gate 14 started September 4, 2012. Wind velocity and direction were measured continuously for one year. Measurement results from 5 minute intervals were processed and summarized to hourly, weekly, monthly and annual data. Correlations between wind measurements from different sources were calculated.

Power output was also measured in 5 min intervals from September 4, 2012 until September 14, 2012 and from June 10, 2013 until October 10, 2013. Measurement results from 5 minute intervals were processed and summarized to hourly, weekly, monthly and annual data. Correlations with wind measurements were made.

In the summer of 2012, detailed noise measurements were obtained by SINTEF IKT and results are presented in section 3.3.

3.1 Wind velocity and direction

Figure 11 shows the results of the wind velocity measurements from the rooftop and the comparison with the weather stations nearby (Blindern and Alna). It can be seen that monthly averages of wind velocity measured at the roof were much lower than the wind velocities measured both at Blindern and Alna. In average, wind velocities on the roof were only 42% of the average measured at Blindern and Alna.

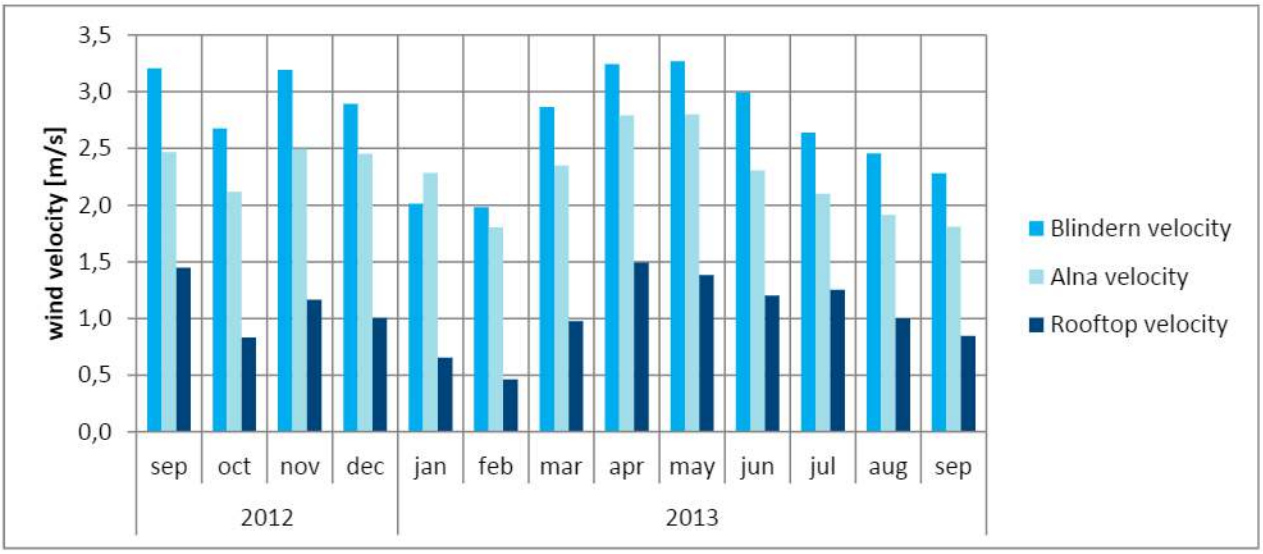

Figure 11: Monthly wind velocities of different measurement stations

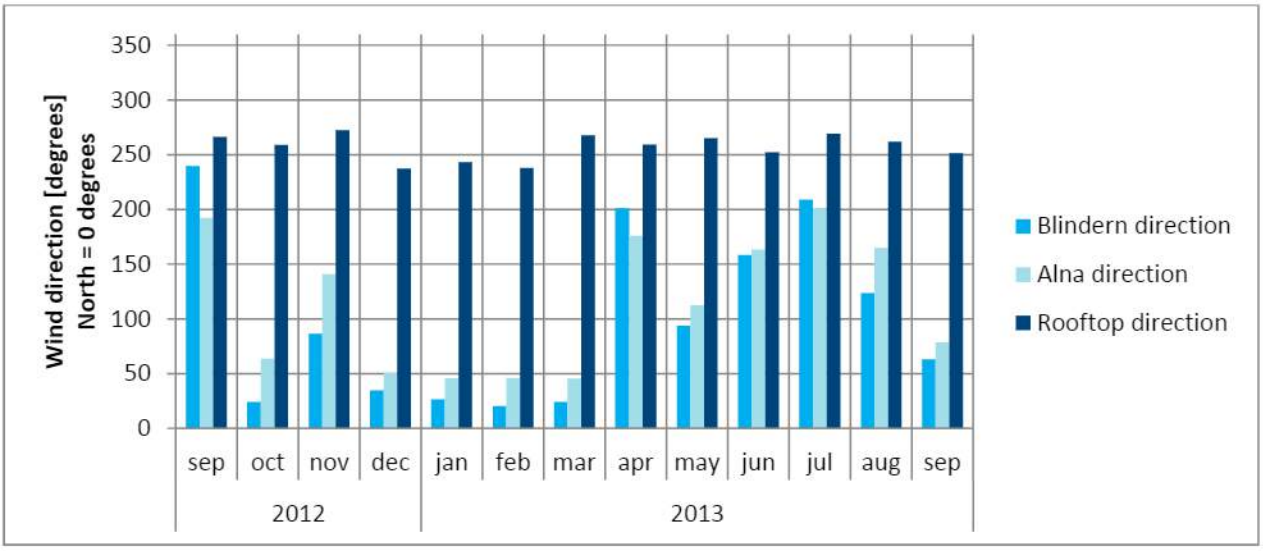

Figure 12: Monthly wind direction for different measurement stations

Figures 12 and 13 illustrate the main wind directions for three different locations in Oslo. Surprisingly, measurements on the roof of Biskop Gunnerus gate 14 show different wind directions than those registered at Alna and Blindern weather stations. There were distinct differences in wind direction between summer (April–August) and winter (October–March). This difference in wind direction was not measured on the roof of Biskop Gunnerus gate 14. Here, the wind direction remained the same throughout the year.

It can be seen in Figure 13 (frequency distribution, below) that measured wind directions from the weather stations at Alna and Blindern were dominating from North and North-North-East (30–60'). The measured wind direction on Biskop Gunnerus gate 14 shows dominance from South-West (270 '). This is difficult to explain. One reason for this mismatch could be local «conditioning» and redirection of wind due to the building geometry and the surroundings.

What might have a major impact is turbulence around the building which would lead to higher gut velocities but lower average wind velocities. The different wind directions (Figure 11) support the presumption that turbulent wind conditions affect the results.

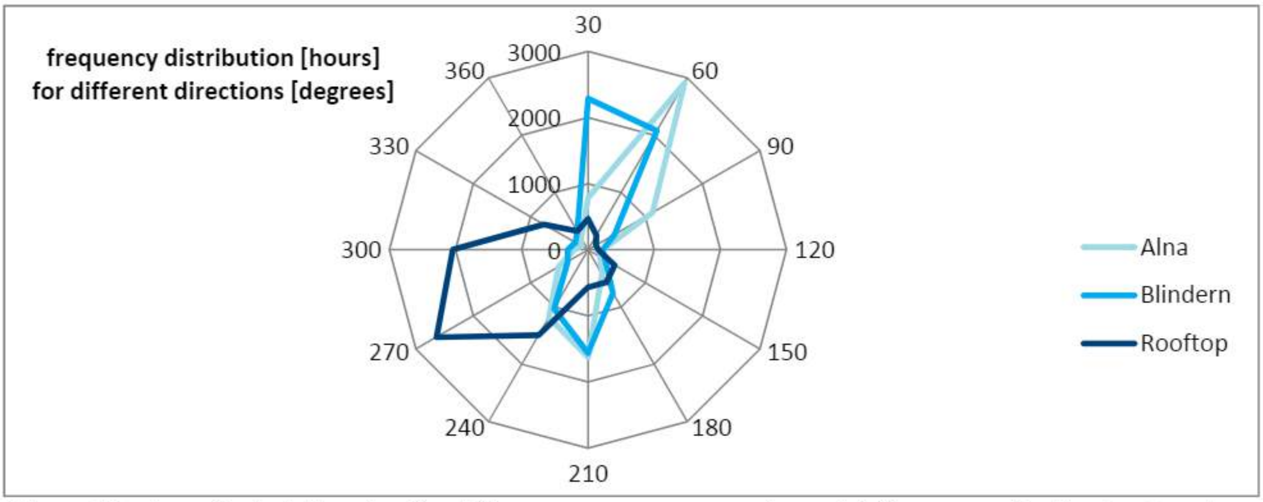

Figure 13: Annual wind direction for different measurement stations with frequency distribution (year)

Table 2: Detailed description of wind velocity calculations

	Location	**Terrain factor**	**Description**
v_{mea}	'Biskop Gunnerus gate 14'	0.35	Measured at roof of Biskop Gunnerus gate 14, 89 m height
v_{calc1}	Based on measurements from weather station Alna	0.21	Calculation based on 10 m height
v_{calc2}	Based on measurements from weather station Blindern	0.21	Calculation based on 28 m height
v_{calc3}	Based on measurements from weather station Alna	0.35	Calculation based on 10 m height
v_{calc4}	Based on measurements from weather station Blindern	0.35	Calculation based on 28 m height

Table 2 explains that the simulations are based on two different weather stations (both at a height of 10 m). The wind velocities were simulated for actual installation height and differences in the urban setting which results in different terrain factors. The results were plotted in Figure 13 to be able to compare (v_{mea} , $v_{calc,\ 1}$, $v_{calc,\ 2}$, $v_{calc,\ 3}$, $v_{calc,\ 4}$,). In table 2 a detailed description of the different values is presented.

Table 2 explains that the simulations are based on two different weather stations (both at a height of 10 m) and two different assumptions for the terrain factor. First, measurements of wind velocity from weather station Alna were used and wind velocities at the roof of the building were calculated (v_{calc1}) with a terrain factor of 0.21. Then, the measurement data from weather station in Blindern was used (v_{calc2}) with a terrain factor of 0.21. The same data from the two weather stations was used with a terrain factor of 0.35 (v_{calc3}, v_{calc4}).

Figure 14 illustrates the results for simulated wind velocities adjusted for height and location (from weather station to Biskop Gunnerus gate 14). It can be seen that even with height corrections, measured wind velocities are much lower than expected in the theoretical calculations.

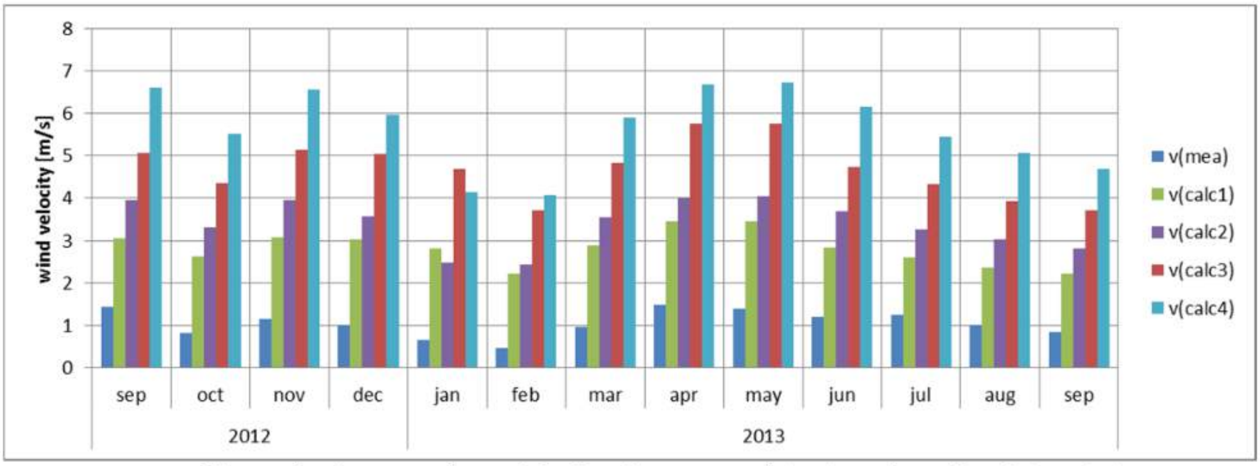

Figure 14: Monthly wind velocities adjusted for height measured (v_{mea}) and simulated (eq. 6) ($v_{calc,\ 1}$, $v_{calc,\ 2}$, $v_{calc,\ 3}$, $v_{calc,\ 4}$)

3.2 Electrical power production

With the equation (eq. 6) monthly power profiles were simulated. Table 3 lists the different simulations, together with the measured wind velocities that were used. In the column to the right, a short description of the simulations is given.

Table 3: Detailed description of energy and power calculations

Energy	Power	Velocity	Description
-	$P_{(mea)}$	-	Measured at rooftop of Biskop Gunnerus gate 14 at 89 m height
$E_{(theo,m)}$	$P_{(theo,m)}$	v_{mea}	Simulated with wind velocities measured on rooftop
$E_{(theo,1)}$	$P_{(theo,1)}$	v_{calc1}	Simulated with wind velocities measured at Alna with terrain factor = 0.21
$E_{(theo,2)}$	$P_{(theo,2)}$	v_{calc2}	Simulated with wind velocities measured at Blindern with terrain factor = 0.21
$E_{(theo,3)}$	$P_{(theo,3)}$	v_{calc3}	Simulated with wind velocities measured at Alna with terrain factor = 0.35
$E_{(theo,4)}$	$P_{(theo,4)}$	v_{calc4}	Simulated with wind velocities measured at Blindern with terrain factor = 0.35

The results are shown in Figure 15 ($P_{mea,}$ $P_{theo,m}$, $P_{theo,1}$, $P_{theo,2}$, $P_{theo,3}$, $P_{theo,4}$, P_{roof}). It can be seen that the theoretical power indicates a rather large potential of power up to 3.7 kW. However, measured power is much lower.

The measurements of power and wind velocity were taken in periods in September 2012 and June to September 2013. Table 4 shows the measured and simulated electric power and the calculated power coefficient c_p which was calculated with (eq.8). It can be seen that c_p-factors vary between 0.9 and 14.3% with an average of 11.4%.

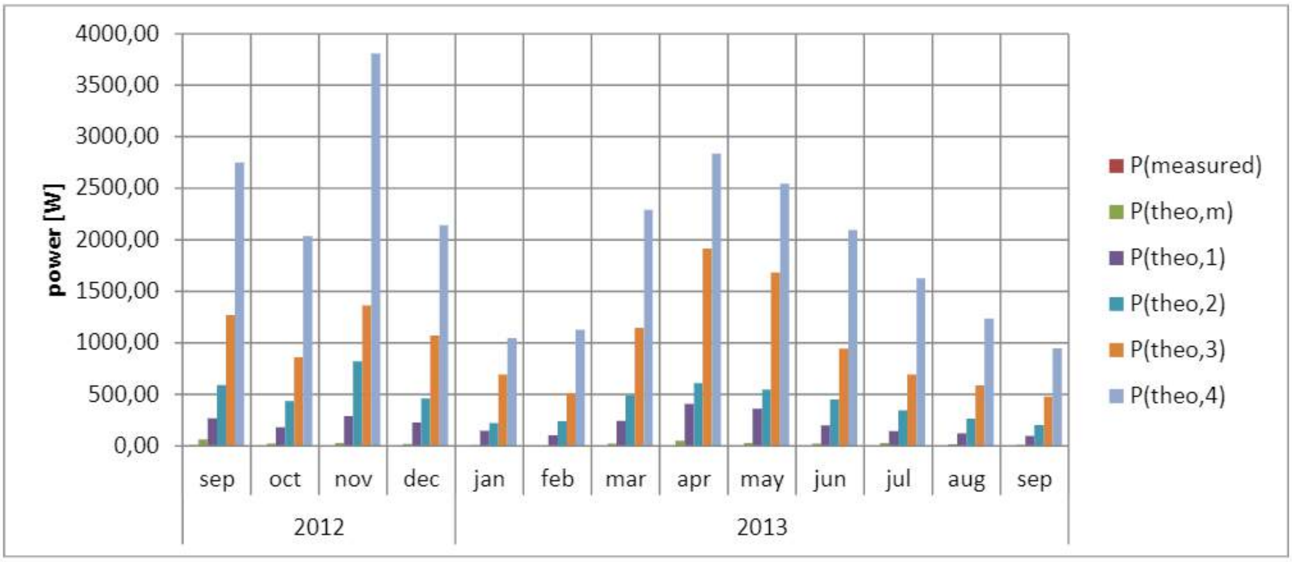

Figure 15: Monthly power vs. wind velocity

Table 4: Power coefficients, c_p, for measurement periods

Period	Power measured P_{mea} [kWh]	Power simulated $P_{theo,m}$ [kWh]	Power coefficient c_p
4.-14.Sep 2012	11,52	80,71	14,3 %
1.-15. Jun 2013	2,52	26,08	9,7 %
16.-30.Jun 2013	0,89	7,93	11,3 %
1.-15. Jul 2013	0,71	10,10	7,1 %
16.-31. Jul 2013	0,65	6,99	9,3 %
1.-15. Sep 2013	0,24	6,18	3,9 %
16.-30. Sep 2013	0,07	7,94	0,9 %
Average (for the above periods)	2,37	20,85	11,4 %

With these measured power coefficients it was possible to simulate electricity production with (eq. 9). Figure 16 shows the measured and simulated energy production with a power coefficient cp = 11%.

Figure 17 gives the simulated annual electricity production $E_{calc,m}$ for different power coefficients. It can be seen that annual electricity production was simulated to 17–22 kWh based on measured wind velocities on the rooftop. This would have been the expected electricity output of the wind turbines if they had run continuously from September 4 to September 30, 2013.

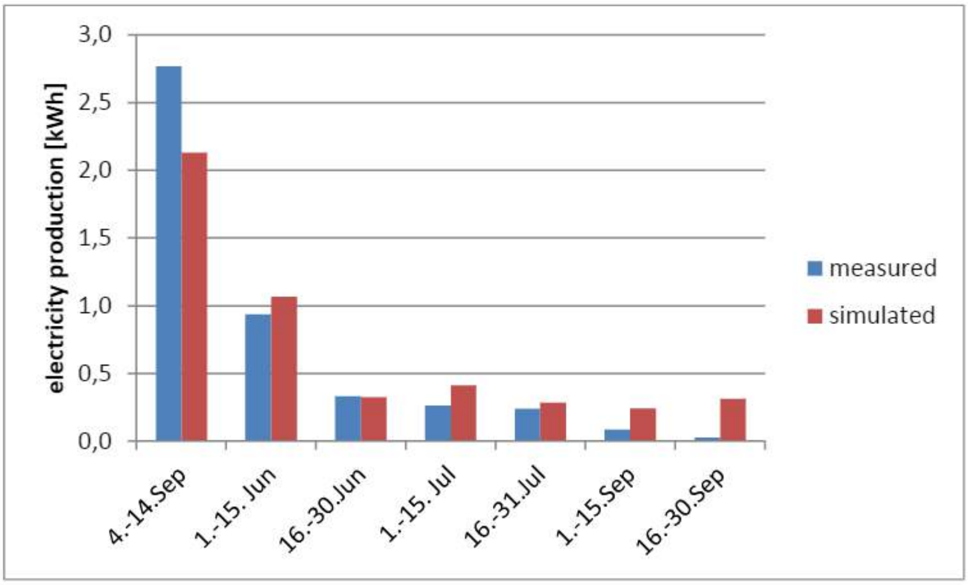

Figure 16: Measured and simulated electricity production in different measurement periods

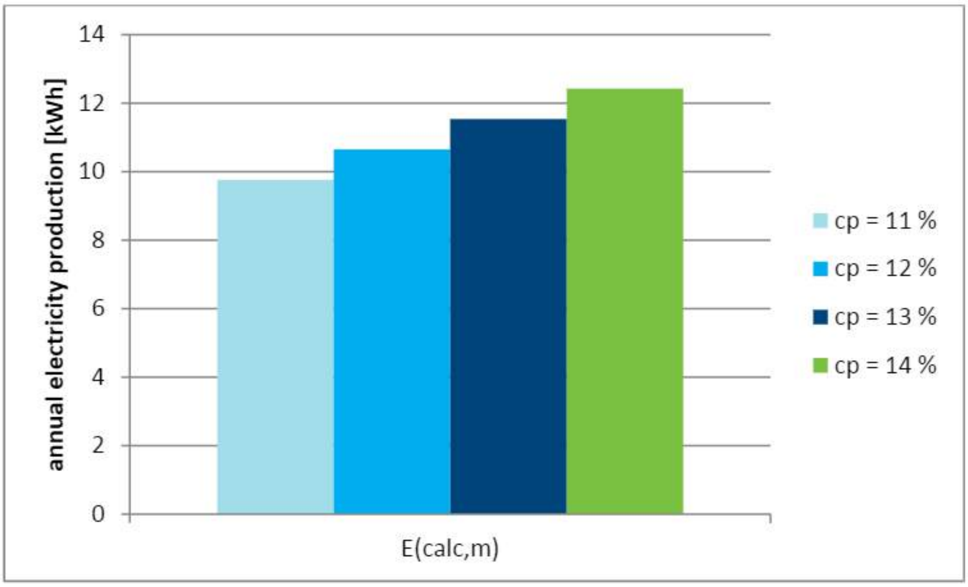

Figure 17: Annual electricity production for different power coefficients cp

Table 5 shows the expected electricity output of the wind turbines for different power coefficients and different wind conditions which were based on the results shown in Figure 13. It can be seen that with higher wind velocities a dramatic increase in electricity production can be expected.

Table 5: Annual electricity production in kWh/year for different wind velocities and different power coefficients cp

Power coeffient c_p	**$E_{calc,m}$**	**$E_{calc,1}$**	**$E_{calc,2}$**	**$E_{calc,3}$**	**$E_{calc,4}$**
11 %	16.9	78,5	430,4	1031,1	2070,2
12 %	18.5	85,6	469,5	1124,8	2258,4
13 %	20.0	92,8	508,6	1218,5	2446,6
14 %	21.6	99,9	547,7	1312,3	2634,8

3.3 Noise

During the noise measurements the wind velocity reached 9 m/s. Technical problems made some of the measurements unreliable, but a regression analysis was performed to make the most of all the data. A detailed description of the regression analysis can be found in Appendix E (Norwegian only).
The radiated sound power level from the wind turbine unit can be seen in Figure 18.

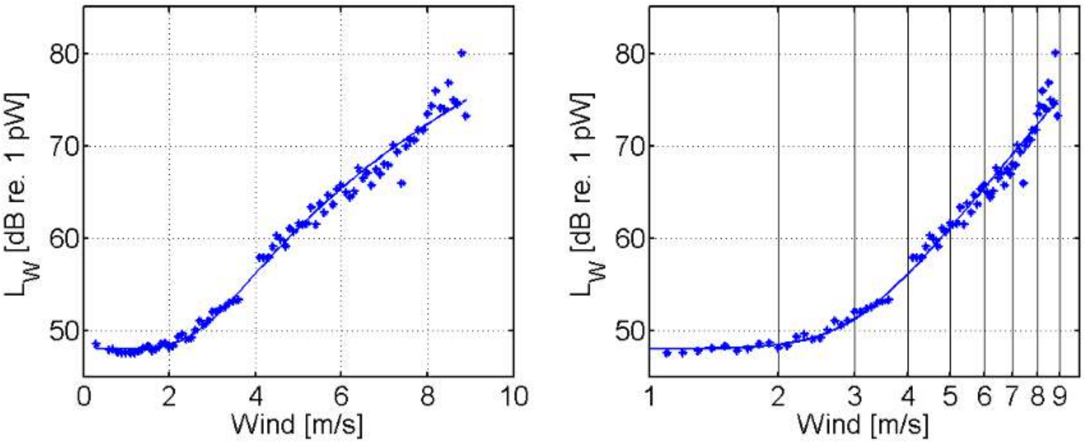

Figure 18: Radiated sound power level from the wind turbine unit as function of wind velocity. Left: Linear x-axis. Right: Logarithmic x-axis.

When radiated noise from wind turbines in general are investigated, a wind velocity of 8 m/s is used. This is because the difference between the noise generated by the wind turbines and the background noise from vegetation is found to be largest at this wind velocity. From the measurements the radiated sound power level is found to be 72.3 dB re. 1 pW at 8 m/s wind velocity. The radiated sound power level can be used to find the sound level at a given point, r meter away from the wind turbine unit, using the following equation:

$$L_p(r) = L_W + 10\log_{10} N - 10\log_{10}(4\pi r^2) = L_W + 10\log_{10} N - 20\log_{10} r - 11,$$

where N is the number of wind turbine units and L_w is the radiated sound power level.

To assess the noise influence on the environment the Norwegian guideline for area planning is used (T-1442/2012). The guideline states that noise from round-the-clock industry should not exceed L_{den} = 55 dBA and L_{night} = 45 dBA. L_{den} is a 24 hours equivalent level with different weighting of day, evening and night noise, and L_{night} is the equivalent level from 23-07. Since the wind turbines will be running 24 hours a day, the L_{night} level will be the hardest criteria to fulfil.

If we use the wind turbine setup from Biskop Gunnerus gate 14 with eight units on top of a roof, the distance where L_{night} = 45 dBA can be found by:

$$\mathrm{d} = 10^{\frac{L_W + 10\log_{10} N - 11 - 45}{20}} = 10^{\frac{72{,}3 + 10\log_{10} 8 - 11 - 45}{20}} = 18.5\ \mathrm{m}$$

In Figure 19 the sound level as a function of distance is shown. The plot shows a worst-case scenario since it assumes a roof mounting where all the wind turbines are visible and placed close to each other.

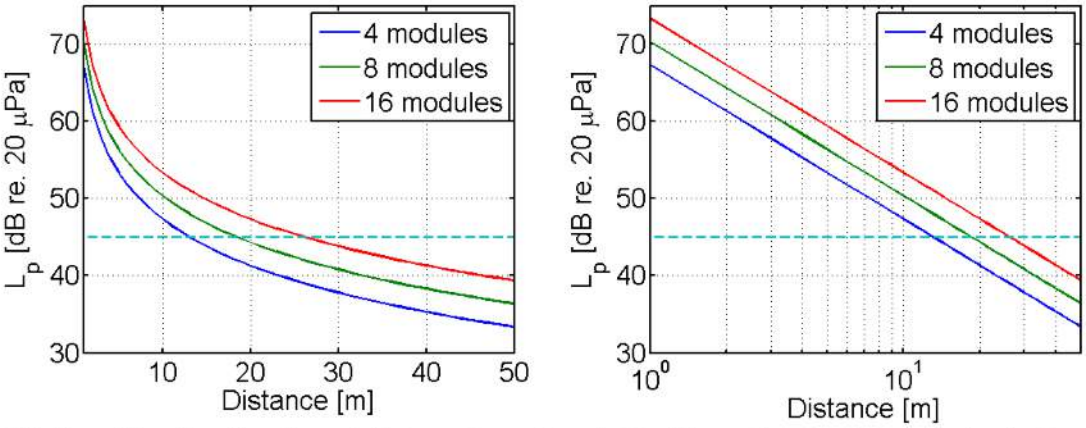

Figure 19: Sound level as function of distance from the wind turbines. Assumptions: wind velocity = 8 m/s, and roof mounting of the wind turbine units. The dashed line shows L_{night} = 45 dBA. Left: Linear x-axis. Right: Logarithmic x-axis.

The conclusion from the noise measurements is that the wind turbine unit(s) will not have negative impact on the sound environment.

4 Discussion

The measurements of wind conditions were continuously monitored between the 4th of September 2012 and end of September 2013. The wind velocity and direction measured at the roof differ greatly from measurements taken at other weather stations in Oslo (Blindern and Alna). The reason for the large differences remains unclear. Local wind conditions on top of the high-rise building Biskop Gunnerus gate 14 must be greatly influenced by the building and its surroundings. More detailed measurements are necessary in order to be able to explain this.

Wind conditions on top of the Biskop Gunnerus gate 14 have been simulated with measured wind data from weather stations nearby. A good agreement between simulations and measurements could be found. However, the roughness of the terrain remains an important parameter as it shows high sensitivity to the wind speed. More detailed measurements are necessary in order to be able to confirm actual roughness of the surroundings (terrain factors).

There was a long period when the wind turbines did not convert energy. Power (and electricity production) could only be measured from September 4 to September 14, 2012 and June to September 2013. In between these periods, the turbines were not in operation. During the time period when the wind turbines were in operation, the electric energy output of the wind turbines was measured to 4.7 kWh. Simulation results show a good agreement between measured and simulated power and electricity production. Thus it was possible to simulate the power and electricity output potential. It became obvious that the wind velocity is the most simportant factor when determining energy production of wind turbines. In the urban built environment, wind conditions are difficult to predict.

Measured wind conditions in Oslo (in all three locations) show average wind speeds that are much lower than what is required for electric operation from the wind turbines. The wind turbine product showed good results on the data sheet (power curve). Since these data depend on standard test conditions, it is advisable to be careful with transferring them to local situations. It is very important to make local measurements of wind conditions (velocity and directions) prior to installation. This can help to select wind turbines that fit to the local wind profile.

The TurboMills product was purchased directly from the producer. However, the producer could not deliver the necessary parts needed to transform the produced current (DC) for the windmill to useful electricity (230V AC). Neither could the batteries necessary to make the system run be delivered. This proved to be a great challenge until the local company Getek AS was engaged. The price of the windmill turned out to be only a small fraction of the installation costs. It had been more convenient to have dealt with only one contractor.

After a couple of weeks of testing the product failed to function during strong wind. The producer had to retrofit the windmills with a brake unit in order to solve this problem. Unfortunately it turned out to be a long and tedious process to receive these retrofit units. The first units delivered did not fit. This was a major setback in the testing, and it took many months to get the windmills up and running again.

The process to obtain allowance from the municipality for the installation was straightforward, since the installation was only temporary.

4.1 SWOT analysis

An analysis of strength, weakness, opportunities and threats (SWOT) was done for vertical axis wind turbines. The aim of a SWOT analysis is to get a better understanding of internal (upper row) and external factors (lower row) that concern such a new technology. It is divided into strength and opportunities in the left column, and weakness and threats in the right column. The table below summarizes the results.

Strengths:	**Weaknesses:**
Relatively simple technology Easy to install on existing buildings Wind might also be available during periods without sunshine (no production from PV) High wind velocities give high energy gains Low noise production	Energy production depends on wind availability Wind velocity in urban settings are often too low for high power outputs Energy production must match demand or a battery is needed (or direct connection with grid) Positioning on buildings requires analysis of local wind conditions A velocity control is needed for very high wind velocities Safety is not always given
Opportunities:	**Threats:**
Emerging technology Increasing environmental awareness increases interest in renewable energy systems	No standards for electrical connection developed Wind resource in the built environment are poorly understood

4.2 Challenges

Measured wind conditions on the roof of the building were very different from expected wind conditions. The location of the measurement devices and the wind turbines in the case study were not optimized. Much lower wind velocities were measured on the rooftop than at the other measurement stations. Correlations show a 40% lower wind velocity on the roof than at the measurement stations. The equivalent wind speed would be even lower if the height of the wind turbine is considered (in accordance with the wind shear power law). This should be taken into consideration when planning to install wind turbines in the built environment.

Accurate prediction of the wind velocity represents the basis for economic performance and is essential to calculate the electricity output of small and micro wind turbines (MWT). Wind evaluation presents challenges due to the relatively high costs of wind measurement tools in urban environments.

The shading and turbulence effect of surrounding obstacles produces inconsistent and unpredictable wind patterns below 30 m. Traditional wind resource maps are rarely available or are inadequate as wind conditions are evaluated at an altitude of 50 m (or 80 m), see also (As, 2003).

The following aspects of the wind resource in the built environment are poorly understood:

- Turbulence and directional variability
- Wakes, eddies, and separation zones
- Three-dimensional wind velocity profile and distribution
- Existing wind resource maps do not translate to the built environment.

As a result, the urgent demand for inexpensive and efficient methods of predicting and collecting local wind data is another key driving factor that requires further development.

Norway has an extensive electric grid, so there is little need for off-grid wind energy systems. However there might be a potential for small grid-connected systems, which Norwegians may find attractive. The high concentration of population in urban areas provides a great opportunity for onsite distributed generation from wind power by installing small wind turbines on rooftops, even though the roughness of the urban environment can mean a reduced and more turbulent wind flow. Because of this, distributed generation based on small wind energy in residential and industrial areas is under development, and urban wind integration seems to be an emerging application that may provide a solution for electricity power demand reduction. Some countries have policies for the promotion of these applications.

Turbomill wind turbine seems not to be suited for the situation it was tested for. Further development work is needed to be able to expoit the full potential.

5 Conclusions

5.1 Wind turbines in the built environment

Many different types of small wind turbines are available on the market. A shift in the energy sector from a centralised energy grid to an ideal distributed network is expected (Smith, et al., 2012). In such a future grid, small wind systems and its hybrid applications can play an increasingly important role. With the support of the smart grid technology, small and micro wind turbines (MWTs) could be connected to the power grid directly at the consumer side and contribute to the stabilisation of the power grid. Small wind application and hybrid technologies have already been put into practice in many countries with some market prospects (small wind report, www.endurancewindpower.com).

An important aspect is the positioning of the MWT in the built environment. Turbulent spots should be avoided. Test measurements of wind velocities and direction prior to installation are highly recommended. The size of the wind turbines in combination with its specific rated power curve can be decisive when choosing the product. It must fit to the measured/projected wind velocities.

Information on and understanding of the wind resource in the built environment is critical for designing MWTs, micro-siting, and estimating the energy production. However, the built environment wind resource is not well understood. Unlike rural environments with few obstructions where we can make adequate estimates for average wind velocity and turbulence, we have limited knowledge that can be applied to wind resources in the built environments. The wind resource is site specific, and in the built environment, there may be large differences among sites due to small differences in the physical properties.

Small vertical wind turbines are relatively easy to install. The costs of such systems need to be evaluated against competing technologies such as photovoltaic systems and CHP systems.

5.2 Suggestions for further work

A much better understanding of wind flow pattern in the city and around buildings and in the urban fabric is needed. Wind condition measurements in the urban environment are definitely needed in order to predict more precisely the wind power potential for specific sites.

Improvement of product quality, establishment of rigorous standards, testing and certification, and lobbying for supportive policies to guarantee the long-term growth of the market is considered important (Smith, et al., 2012).

Internationally accepted IEC standards (IEC61400) relevant to the small wind turbine industry already exist, but are not much used. Some effort is required to develop the existing standards for SWTs, in order to make them more widely used. For instance, the IEC 61400-2 standard «Design requirements for small wind turbines», which applies to wind turbines with a rotor swept area smaller than 200 m^2 and generating at a voltage below 1,000 Vac (Volts Alternating Current) is difficult and costly to apply; this standard is under revision in order to cope with these obstacles. Finally, when the intent of including noise measurements in the standard rating system is agreed upon, the test procedure outlined needs further development and standardization.

Safety is the most critical barrier to widespread use of MWT. MWTs are installed on or in close proximity to buildings, people, and infrastructure. A catastrophic failure could damage property, injure people, and tarnish the wind industry's image.

The barriers are characterized by a need for better understanding of the wind resource and turbines designed for that resource. Turbines must be developed with respect to:

- Fatigue resistance
- Braking redundancy
- Fail-safe features
- Strategies for ice- and part-shedding containment.

When MWTs are mounted to buildings, interactions with buildings are a major design and siting concern. Furthermore, whether they are attached to or detached from the building structure, MWT systems have electrical integration considerations. The barriers regarding building interactions are further complicated by the multitude of building types and locations. Concerns include not only mounting the MWT on buildings, but also:

- Resonance frequencies
- Code compliance
- Mechanical and electrical integration
- Architectural considerations

6 References

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A Appendix – Wind and power measurements

A.1 Measurements

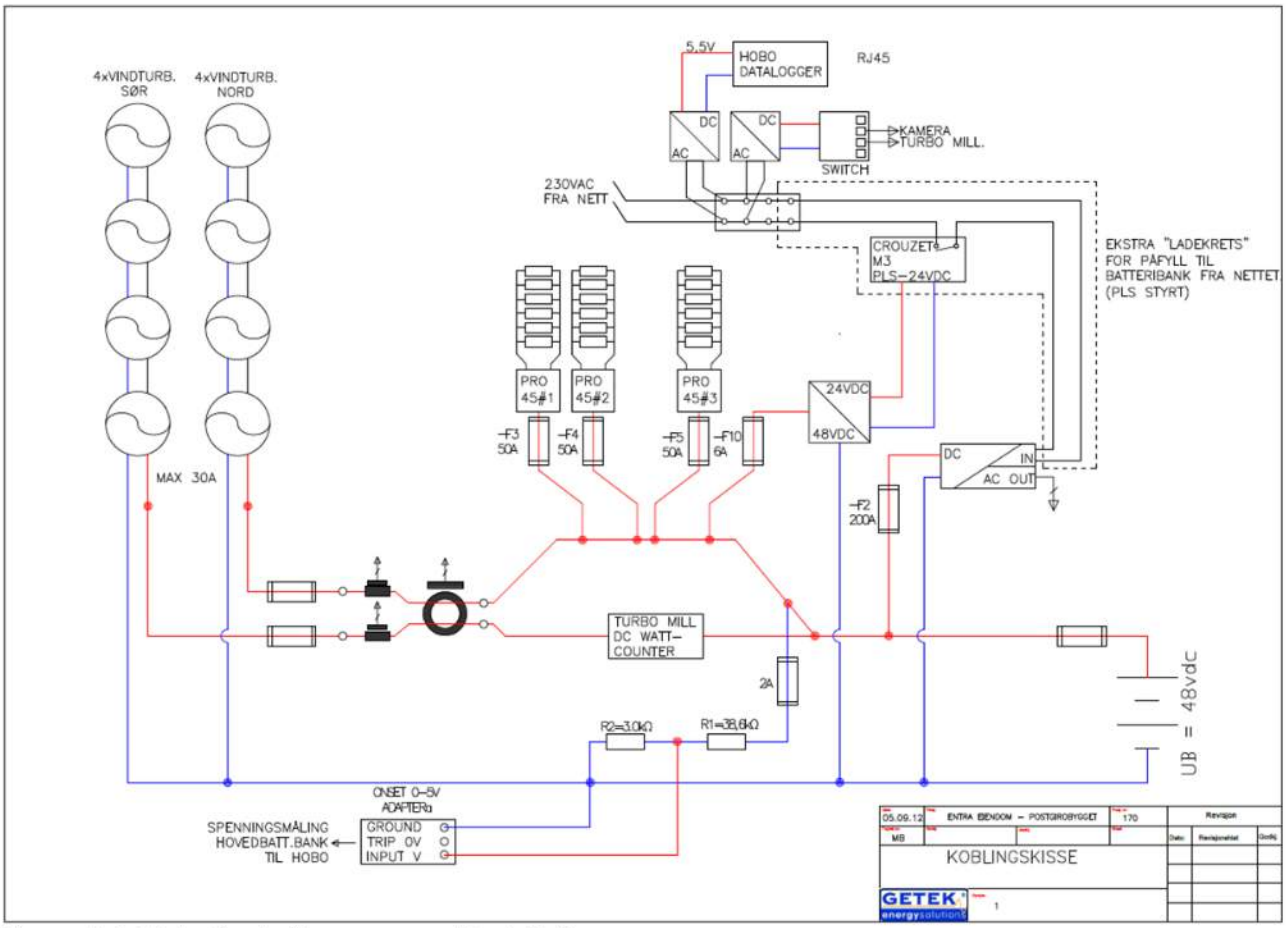
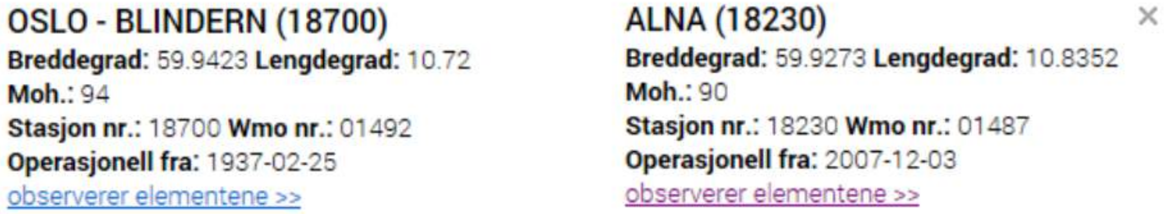


Figure A.1: Data sheet of measurement installation

A.2 Weather stations



OSLO - BLINDERN (18700)
Breddegrad: 59.9423 **Lengdegrad:** 10.72
Moh.: 94
Stasjon nr.: 18700 **Wmo nr.:** 01492
Operasjonell fra: 1937-02-25
observerer elementene >>

ALNA (18230)
Breddegrad: 59.9273 **Lengdegrad:** 10.8352
Moh.: 90
Stasjon nr.: 18230 **Wmo nr.:** 01487
Operasjonell fra: 2007-12-03
observerer elementene >>

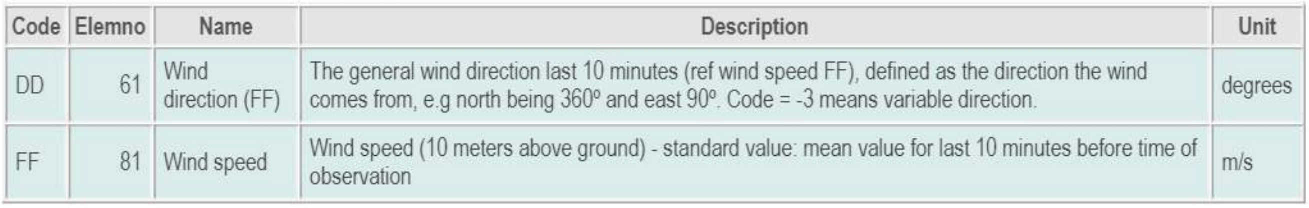
Figure, A.2: Weather stations details

The Norwegian weather stations are classified according to the system in Appendix A.3.

- At Blindern (18700), wind is measured at 28 m.
- The station at Alna (18230) measures wind at 10 m height.

From the weather stations, the available wind data timeseries are FF and DD, which are the mean values for the last 10 minutes before time of observation (every hour). The rooftop measurements are constructed into hourly timeseries from the mean values of each recorded 10 minute intervall.

Table A.2: Elements from eklima.no



Code	Elemno	Name	Description	Unit
DD	61	Wind direction (FF)	The general wind direction last 10 minutes (ref wind speed FF), defined as the direction the wind comes from, e.g north being 360º and east 90º. Code = -3 means variable direction.	degrees
FF	81	Wind speed	Wind speed (10 meters above ground) - standard value: mean value for last 10 minutes before time of observation	m/s

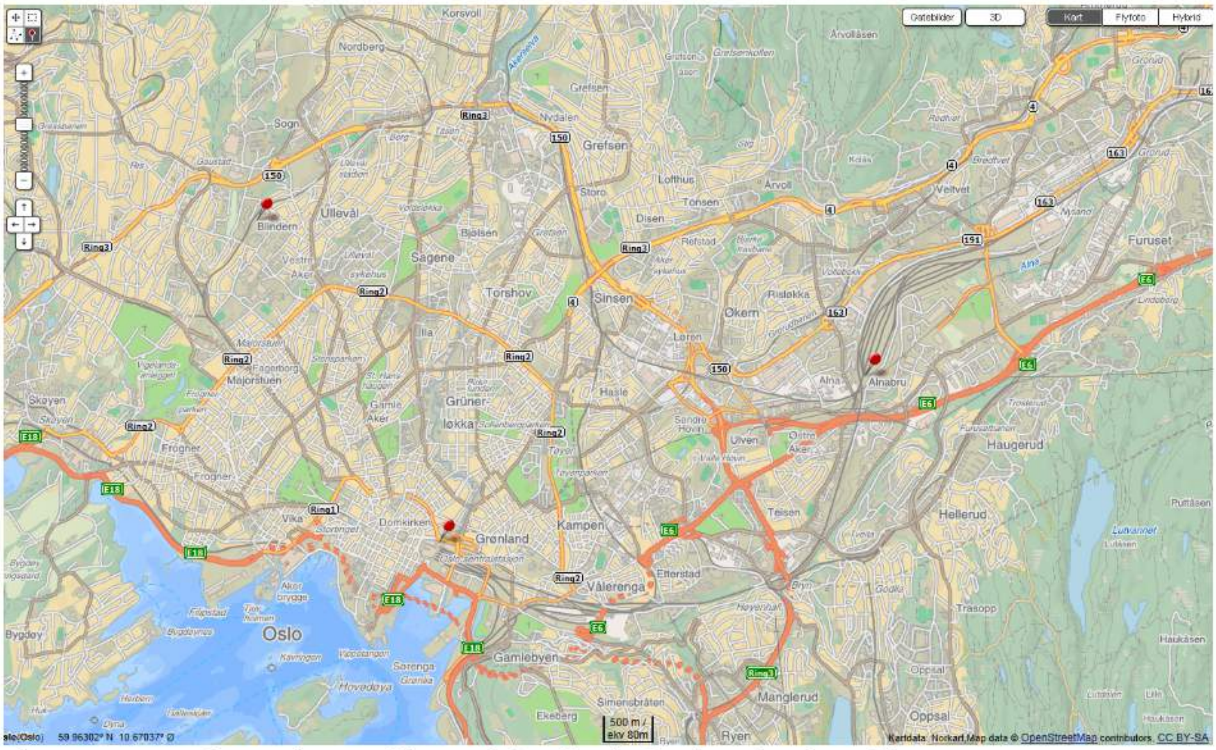


Figure A.3: Weather stations position and situation in the city related to Biskop Gunnerus gate 14

Figure A.4: Weather station Alna (18230), industry area, looking east (nearest hill north and east).

Figure A.5: Weather station Alna (18230), industry area, looking north (google/maps)

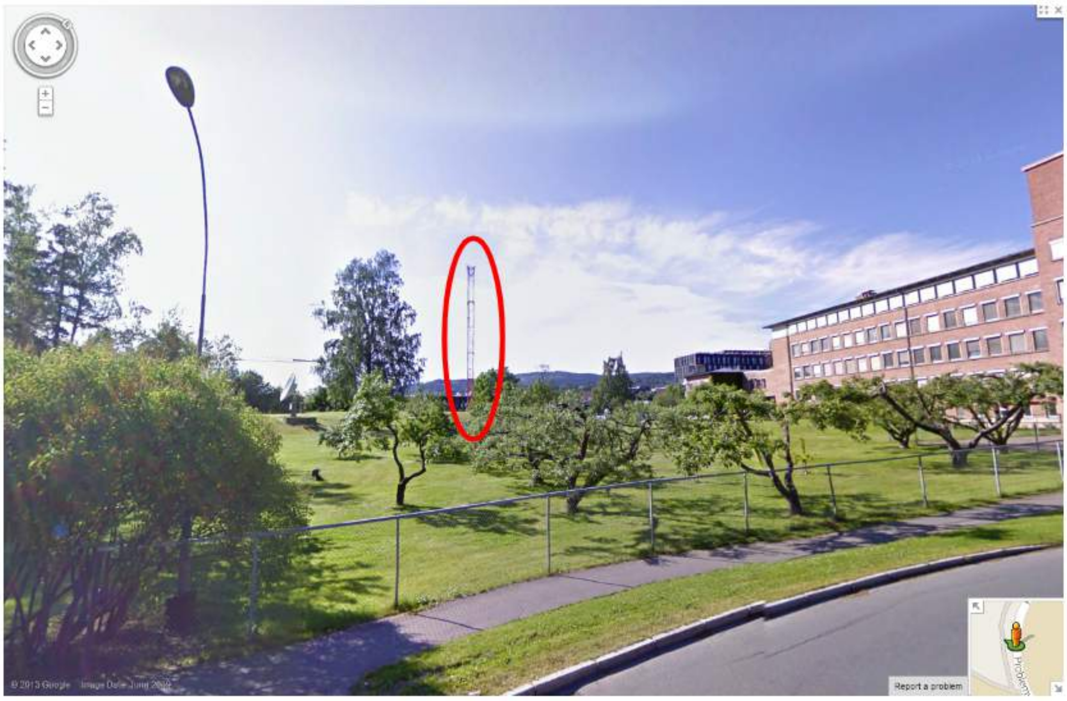


Figure A.6: Weather station Bindern 18700. University buildings and low rise urban environment, looking towards the nearest hill to the north. The wind measurements are taken in 28 m height, due to the proximity of nearby buildings.

A.3 Wind classification

Norwegian weather stations are chategorized after a classification system 1–5.

- At Blindern (18700), the classification is category 3, where 1 would be ideal conditions (flat terrain, no nearby obstructions).
- The station at Alna (18230) measures wind at 10 m height. The station has not been chategorized, but the classification is probably no better than chategory 3.

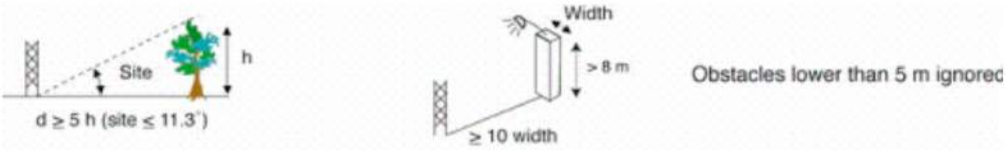
The following description of the classification system can be found in Norwegian (www.met.no):

Klassifiseringen er beregnet for vindmåling i 10 m høyde. Hvis måleren er montert lavere, er vurderingen klasse 4 og 5 med flagg S (spesiell situasjon). Hvis flere hindringer større enn 2 m forekommer i området, er det anbefalt å plassere vindmåleren 10 m høyere enn hindringenes midlere høyde. For klassifiseringen regnes da høyden av hindringene som den delen som er over nivået 10 m under sensor. (For eksempel med vindsensor montert 13 m over bakken er klassifiseringssystemets «bakkenivå» å regne som 3 m, og en hindring av 7 m er å betrakte som effektiv 4 m høy.)

Variasjoner i landskapet som ikke er representative, er betraktet som hindringer.

Kriterier for klasse 3

- Avstanden til hindringer er minst fem ganger hindringens* høyde.
- Avstanden til tynne hindringer (mast, tynne trær, høyere enn 8 m) er minst 10 ganger hindringens bredde



*hindringer lavere enn 5 m blir ikke tatt i betraktning

A.4 Density of air

$$\rho_H = \rho_0 \frac{T_0}{273,15\, t} \frac{p_H}{p_0}$$

with:

ρ_H = air density in height H above N. Z.

ρ_0 = air density in height N. Z. (ρ_0 = 1.225 kg/m^3)

T_0 = 288.15 K at 5°C in height N.Z.

P_0 = air pressure in height N.Z. (p_0 = 1013.3 mbar)

t = Temperature in height H (°C)

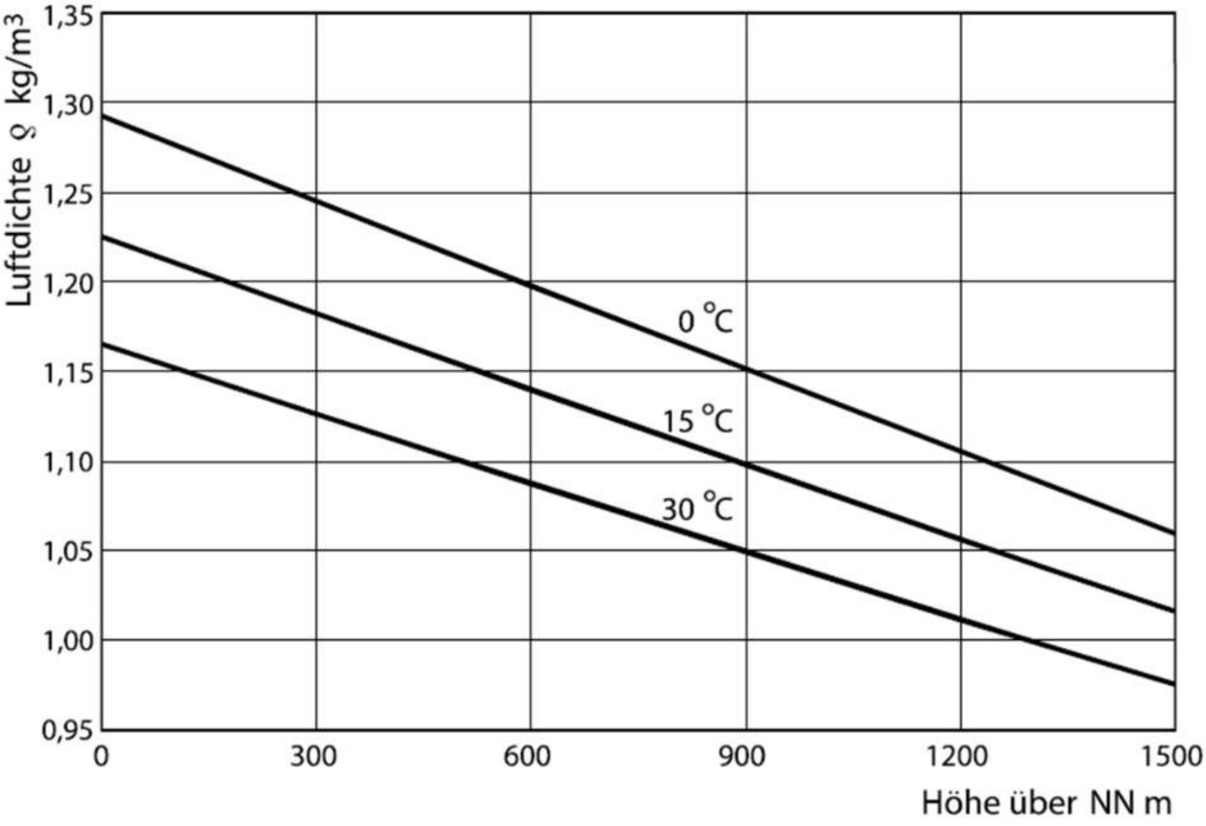


Bild 14.16: Luftdichte in Abhängigkeit von der geographischen Höhenlage und der Temperatur

Figure A.7: Air density in relation to height and temperature (Hau)

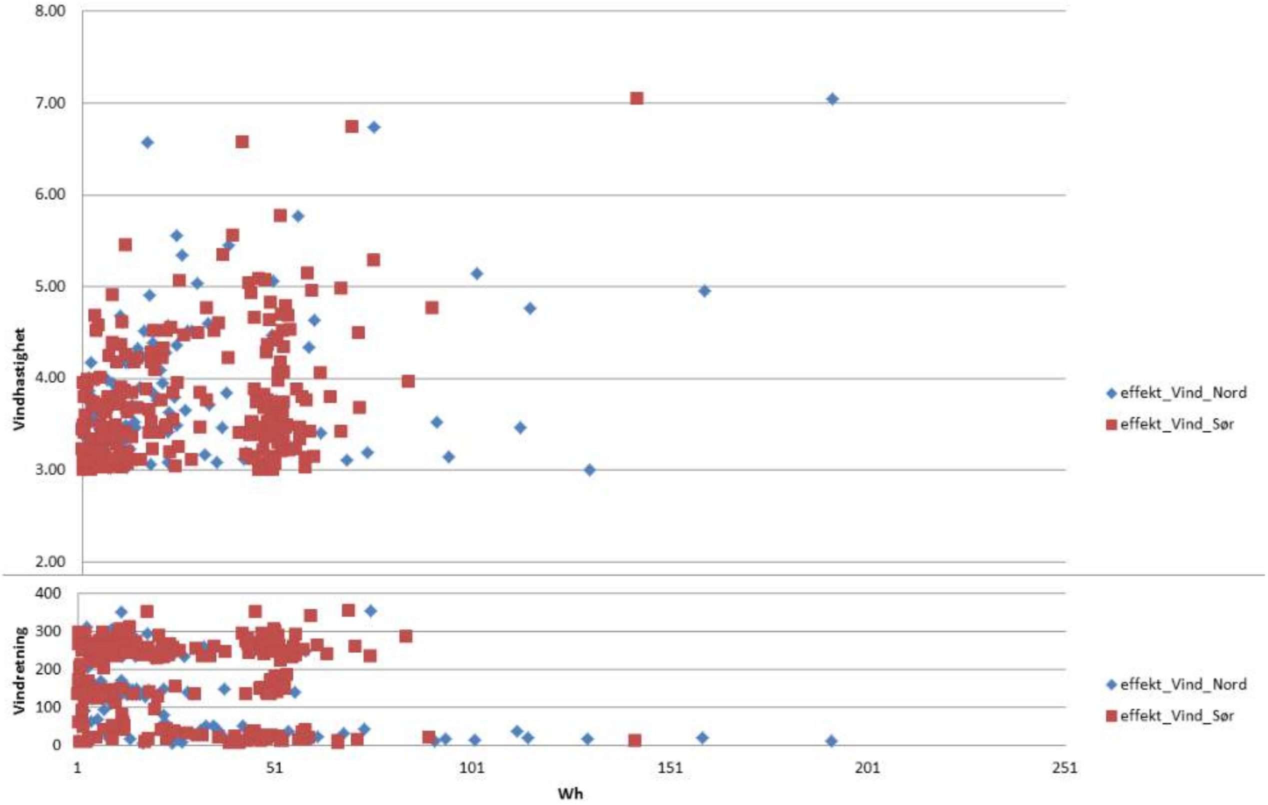


Figure A.8: Hourly power vs. wind velocity and direction

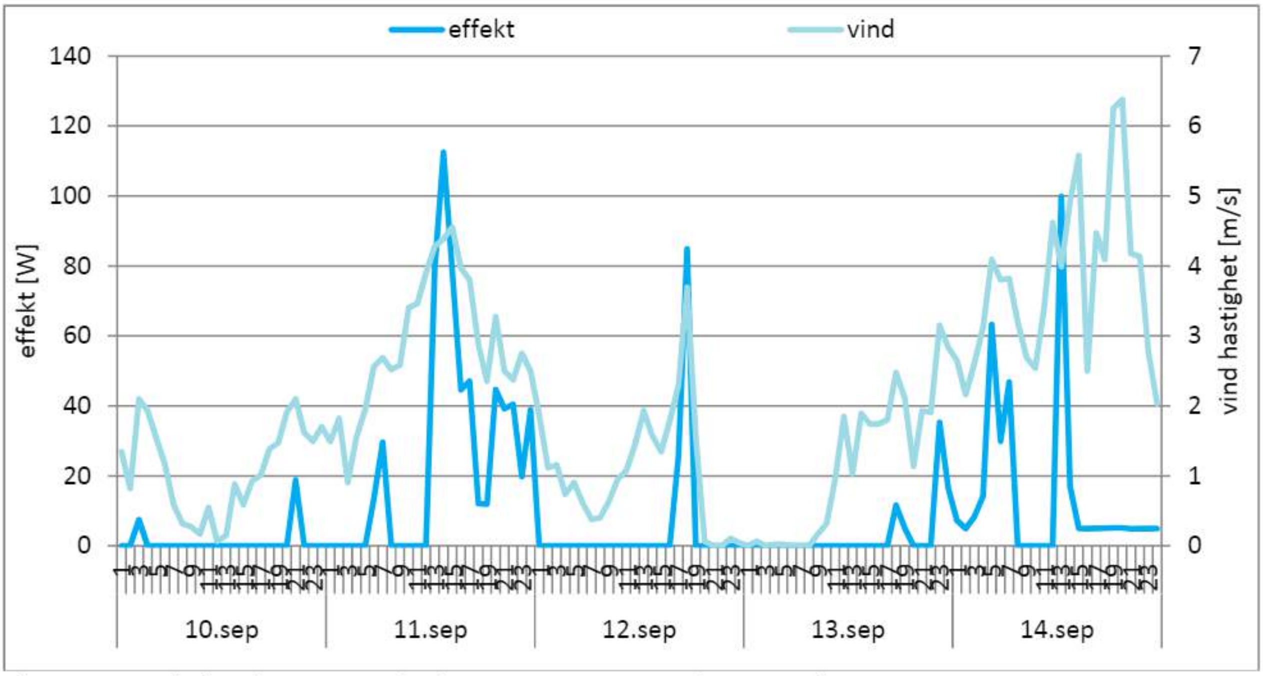


Figure A.9: Wind and power production measurement results September 10.–14. 2012

B Appendix – Wind turbines installation and power curves

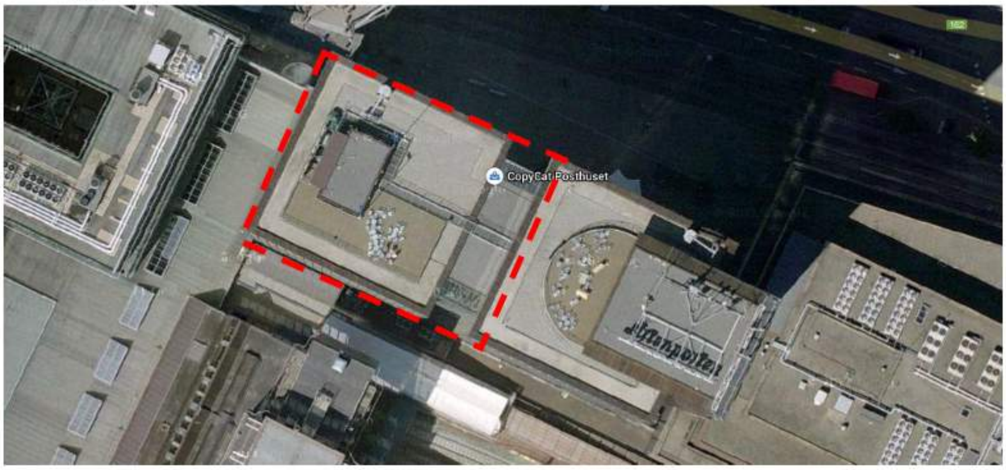


Figure B.1: Plan view of Biskop Gunnerus gate 14 building with roof area (www.google.com/maps). Marked area (red) shows plan in figure B.2

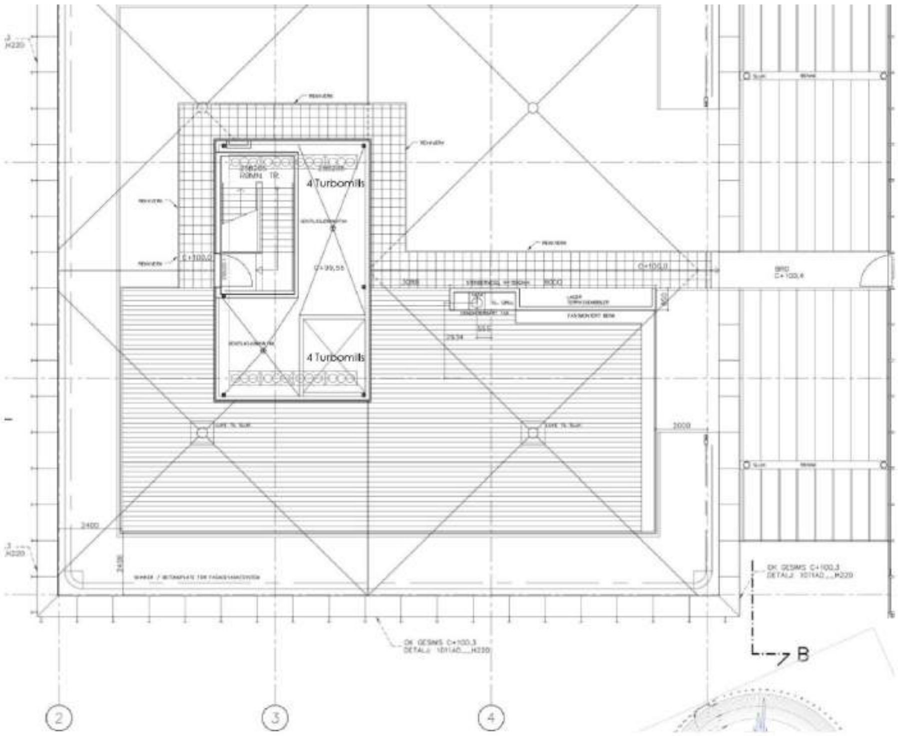
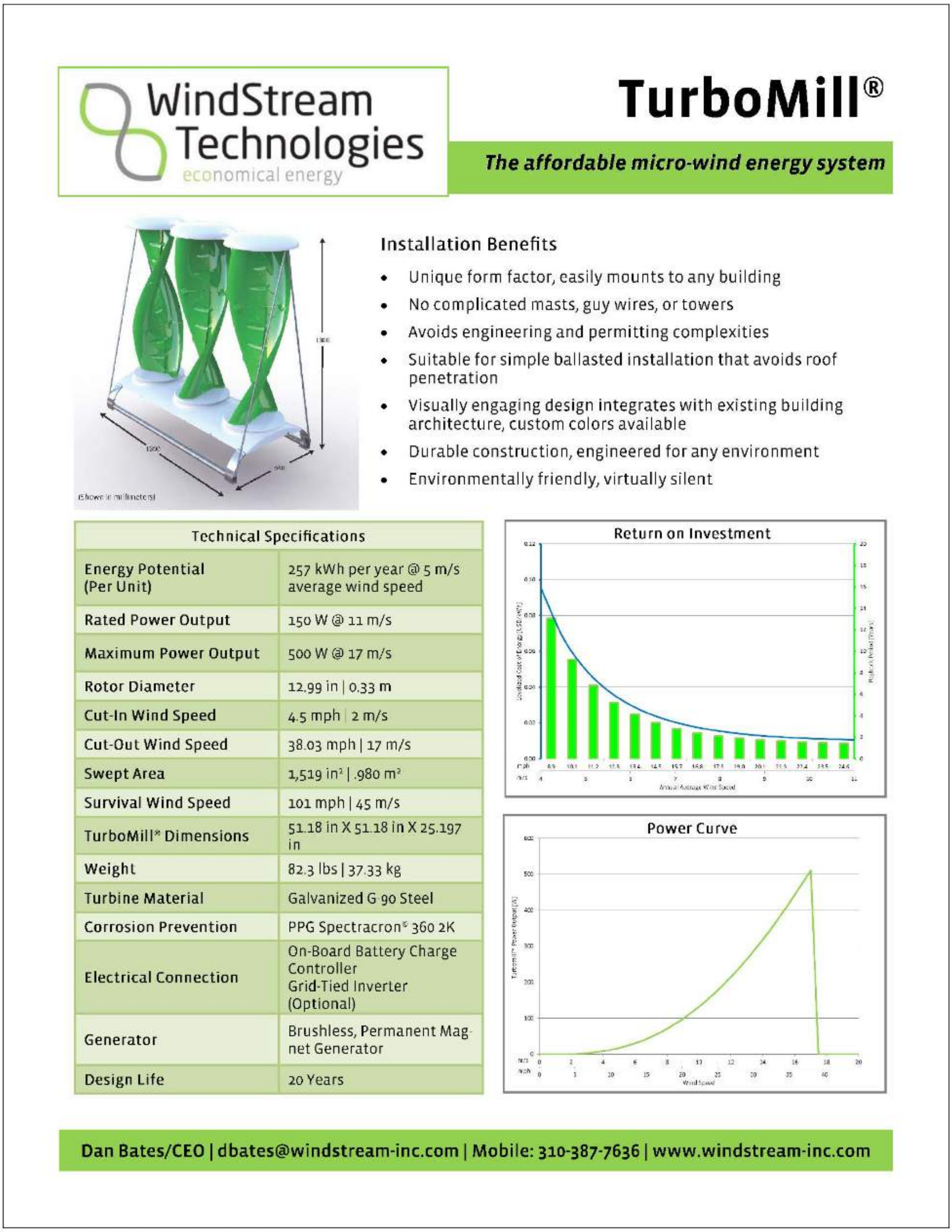


Figure B.2: Plan of roof area with sketch of rows of installed wind turbines



WindStream Technologies
economical energy

TurboMill®

The affordable micro-wind energy system

Installation Benefits

- Unique form factor, easily mounts to any building
- No complicated masts, guy wires, or towers
- Avoids engineering and permitting complexities
- Suitable for simple ballasted installation that avoids roof penetration
- Visually engaging design integrates with existing building architecture, custom colors available
- Durable construction, engineered for any environment
- Environmentally friendly, virtually silent

Technical Specifications	
Energy Potential (Per Unit)	257 kWh per year @ 5 m/s average wind speed
Rated Power Output	150 W @ 11 m/s
Maximum Power Output	500 W @ 17 m/s
Rotor Diameter	12.99 in | 0.33 m
Cut-In Wind Speed	4.5 mph | 2 m/s
Cut-Out Wind Speed	38.03 mph | 17 m/s
Swept Area	1,519 in² | .980 m²
Survival Wind Speed	101 mph | 45 m/s
TurboMill® Dimensions	51.18 in X 51.18 in X 25.197 in
Weight	82.3 lbs | 37.33 kg
Turbine Material	Galvanized G-90 Steel
Corrosion Prevention	PPG Spectracron® 360 2K
Electrical Connection	On-Board Battery Charge Controller Grid-Tied Inverter (Optional)
Generator	Brushless, Permanent Magnet Generator
Design Life	20 Years

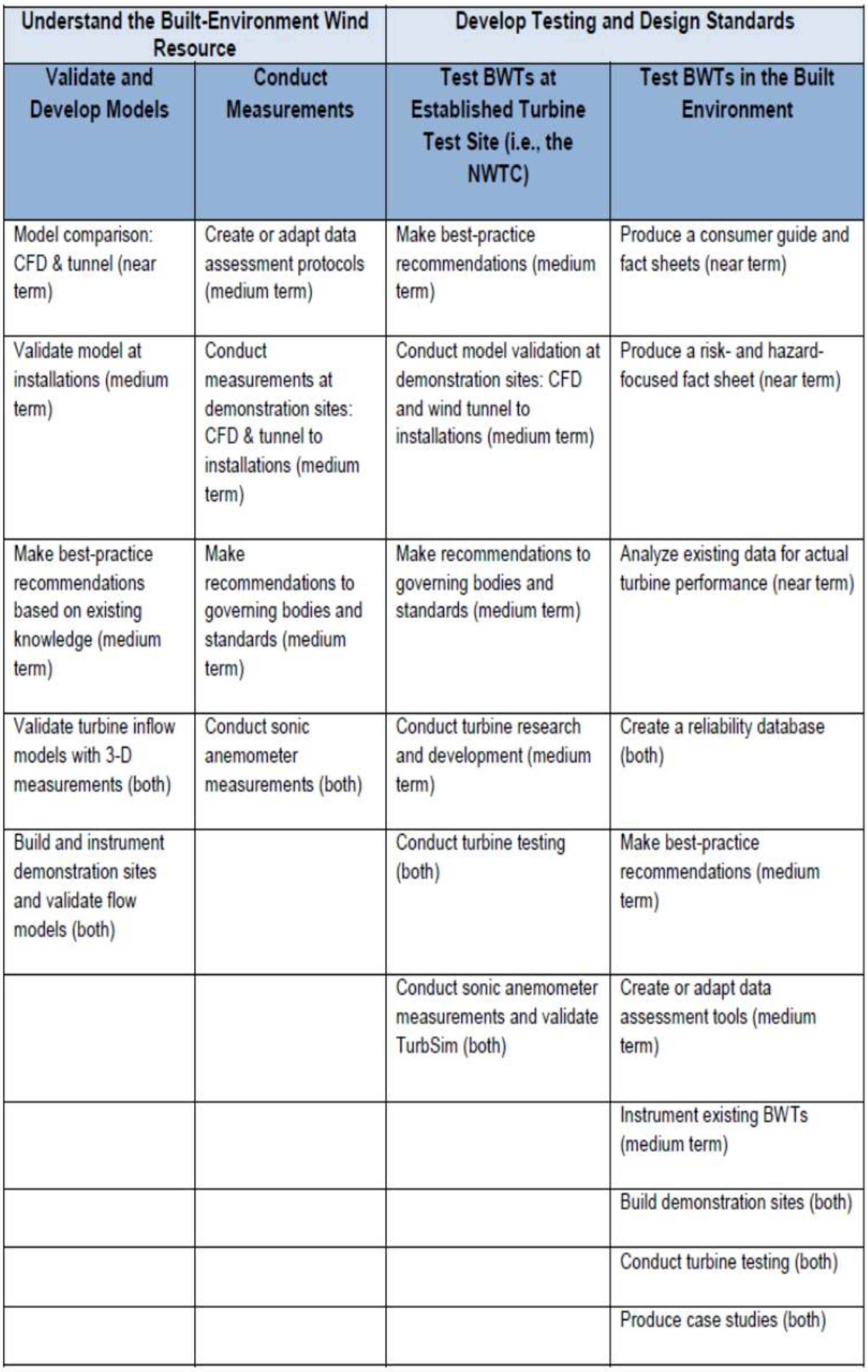
Return on Investment

Power Curve

Dan Bates/CEO | dbates@windstream-inc.com | Mobile: 310-387-7636 | www.windstream-inc.com

Figure B.3: Data sheet of wind turbines used

C Appendix – Strategy



Understand the Built-Environment Wind Resource		Develop Testing and Design Standards	
Validate and Develop Models	**Conduct Measurements**	**Test BWTs at Established Turbine Test Site (i.e., the NWTC)**	**Test BWTs in the Built Environment**
Model comparison: CFD & tunnel (near term)	Create or adapt data assessment protocols (medium term)	Make best-practice recommendations (medium term)	Produce a consumer guide and fact sheets (near term)
Validate model at installations (medium term)	Conduct measurements at demonstration sites: CFD & tunnel to installations (medium term)	Conduct model validation at demonstration sites: CFD and wind tunnel to installations (medium term)	Produce a risk- and hazard-focused fact sheet (near term)
Make best-practice recommendations based on existing knowledge (medium term)	Make recommendations to governing bodies and standards (medium term)	Make recommendations to governing bodies and standards (medium term)	Analyze existing data for actual turbine performance (near term)
Validate turbine inflow models with 3-D measurements (both)	Conduct sonic anemometer measurements (both)	Conduct turbine research and development (medium term)	Create a reliability database (both)
Build and instrument demonstration sites and validate flow models (both)		Conduct turbine testing (both)	Make best-practice recommendations (medium term)
		Conduct sonic anemometer measurements and validate TurbSim (both)	Create or adapt data assessment tools (medium term)
			Instrument existing BWTs (medium term)
			Build demonstration sites (both)
			Conduct turbine testing (both)
			Produce case studies (both)

Strategy for wind turbine development [SMITH]

D Appendix – Wind power theory

Table D.1: Terrain and wind shear factors

Terrain / wind shear factor	c	α
Open flat country	0.68	0.167
Country with scattered wind breaks	0.52	0.2
Urban	0.35	0.25
City	0.21	0.33

E Appendix – Noise report (in Norwegian)

SINTEF

SINTEF IKT
Postadresse:
Postboks 4760 Sluppen
7465 Trondheim

Sentralbord: 73593000
Telefaks: 73594302

postmottak.IKT@sintef.no
www.sintef.no
Foretaksregister:
NO 948 007 029 MVA

Prosjektnotat

TurboMill

Støypåvirkning til omgivelsene

VERSJON
1.0

DATO
2012-12-06

FORFATTER(E)
Tron Vedul Tronstad
Svein Ådne Storeheier
Frode Haukland

OPPDRAGSGIVER(E)
SINTEF Byggforsk

OPPDRAGSGIVERS REF.
Matthias Haase

PROSJEKTNR
3B071004

ANTALL SIDER OG VEDLEGG:
13 + vedlegg

SAMMENDRAG

På oppdrag fra SINTEF Byggforsk har vi, SINTEF IKT Akustikk, vurdert støypåvirkning til omgivelsene fra vindturbiner installert på taket av to bygninger, én i Oslo og én i Trondheim. Dette har blitt gjort ved å gjøre en kildeklassifisering av én vindturbin-modul. Denne har så blitt brukt til å vurdere mulig støypåvirkning.

Vindturbinene er av typen TurboMill, produsert av WindStream Technologies.

UTARBEIDET AV
Tron Vedul Tronstad

SIGNATUR

GODKJENT AV
Odd Kr. Ø. Pettersen

SIGNATUR

PROSJEKTNOTAT NR
3B071004

GRADERING
Fortrolig

Historikk

VERSJON	DATO	VERSJONSBESKRIVELSE
1.0	2012-10-09	Første versjon

Innholdsfortegnelse

BILAG/VEDLEGG

1 Introduksjon

SINTEF IKT Akustikk fikk i oppdrag av SINTEF Byggforsk, med kontaktperson Matthias Haase, å gjøre en støyutredning av mindre vindturbiner som skal monteres på taket av to bygninger. Den ene bygningen er i Biskop Gundersens gate 14A, i Oslo, også kjent som Postgirobygget, den andre er på Brattørkaia 17B i Trondheim.

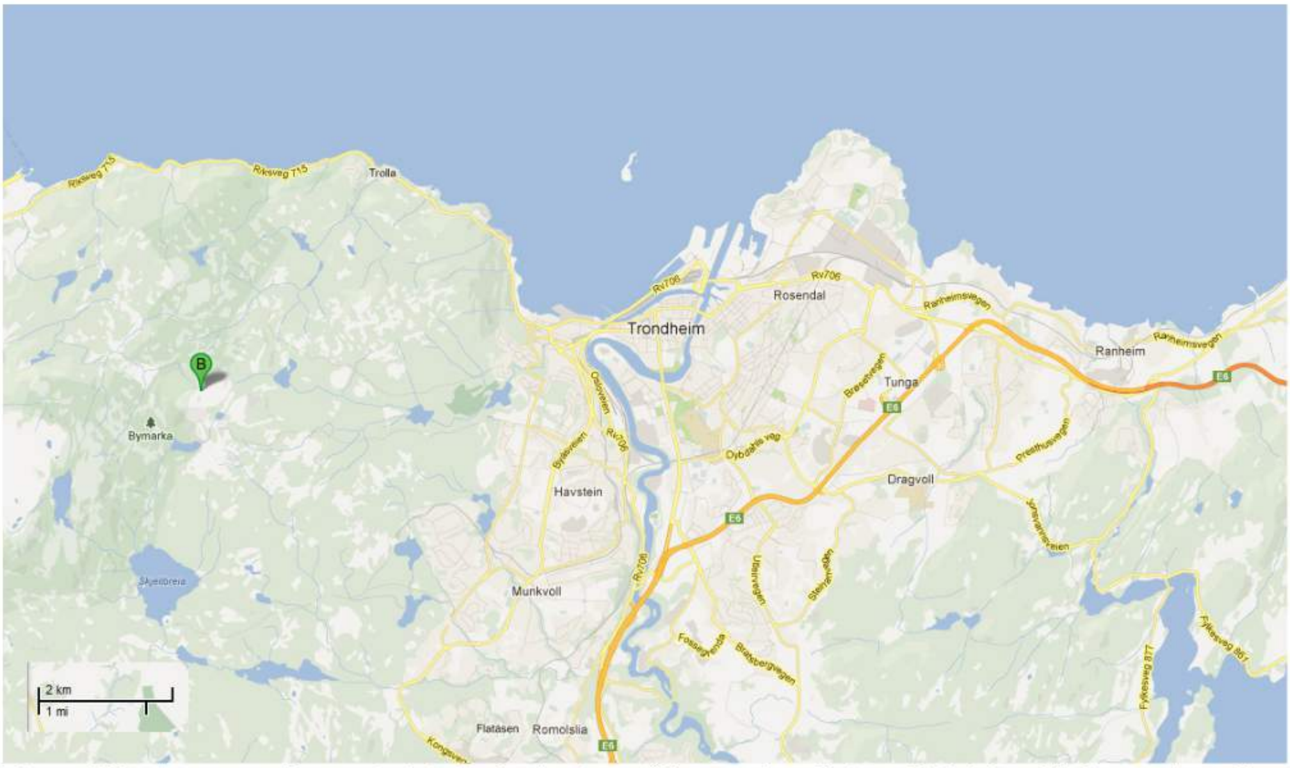
For å kunne vurdere hvorvidt vindturbinen kunne ha negativ innvirkning på omgivelsene, støymessig, måtte vi gjøre en kildeklassifisering. Basert på denne ble det gjort en vurdering om videre støykartlegging var nødvendig.

Vindturbinen som skulle utredes var av typen TurboMill (se vedlegg) og er relativt liten (130x64x130 cm, LxBxH). Den består av tre rotorer med vertikal rotatsjon. For å få gode kildedata fra vindturbinen trengte vi et åpent område med relativt mye vind og lite bakgrunnsstøy. Områder nært fjelltopper tilfredsstiller ofte disse kriteriene pga. mye vind og lite vegetasjon og andre objekter som kan bidra til bakgrunnsstøy. Det er i tillegg sjelden andre støyende kilder (trafikk, industri, etc.) nær fjelltopper.

2 Kildeklassifisering

For å kunne vurdere hvorvidt vindturbinene kan påvirke omgivelsene var det viktig å få målt hvor mye støy de utstråler under ulike forhold. En slik kildeklassifisering avklarer også hvorvidt det er nødvendig å generere støykart rundt de aktuelle bygningene, eller om man kan konstatere at andre støykilder (trafikk, ventilasjonsanlegg, vind, etc.) vil overdøve støyen som kommer fra vindturbinene.

Kildeklassifiseringen vi gjorde ble utført rett under toppen av Gråkallen i Trondheim, inne på det militære området. Perioden målingene ble gjennomført var uke 41 og 42, 2012. I Figur 1 er et kart som viser stedet vi benyttet.

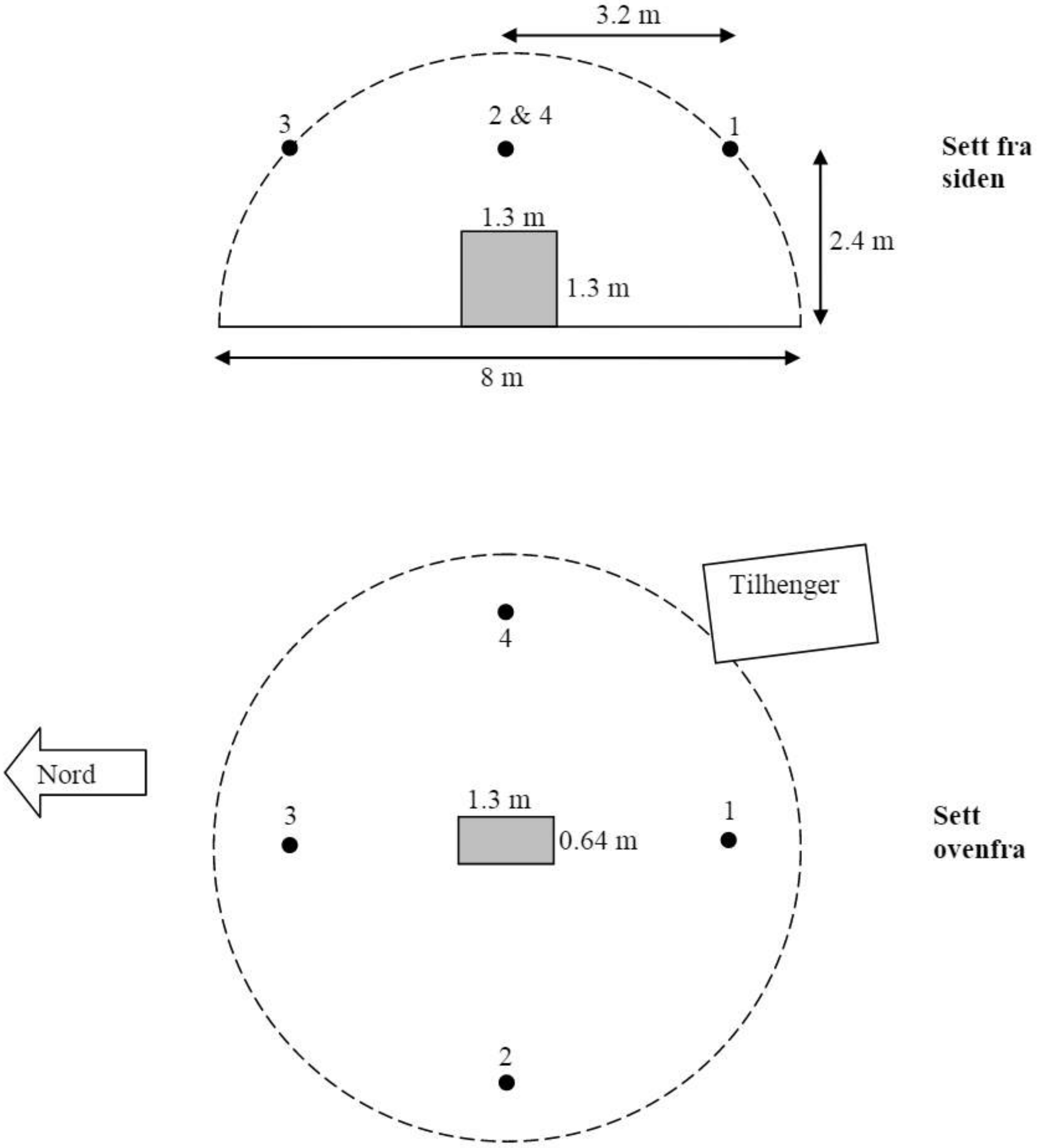


Figur 1 Kart som markerer stedet vi gjorde støymålingene (merket med B). Trondheim sentrum kan sees midt i bildet.

2.1 Måleoppsett

For å gjøre kildeklassifiseringen benyttet vi et måleoppsett kalt *NORDTEST sfærisk metode* beskrevet i NT ACOU 080 [1]. Dette oppsettet beregner utstrålt lydeffekt basert på fire målepunkt rundt kilden. Plasseringen av målemikrofonene blir bestemt av størrelsen til kilden. Det fysiske måleoppsettet som ble definert av vindturbinen kan sees i Figur 2. Som man kan se er diameteren til målesfæren 8 meter, og målemikrofonene ble plassert i en høyde på 2.4 meter.

For å oppbevare måleutstyr ble en tilhenger med lokk benyttet. På grunn av lengden på kablene vi benyttet måtte tilhengeren plasseres i nærheten av målesfæren. Siden et slikt stort objekt vil kunne gi refleksjoner til målemikrofonene ble tilhengeren snudd slik at ingen flater kunne gi en direkte refleksjon til noen av mikrofonene.



Figur 2 Måleoppsett for kildekarakterisering av vindturbin. Grå boks er vindturbinen. Sorte prikker er plassering av målemikrofoner. Selve kuleoverflata er bare en virtuell flate som brukes til å beregne utstrålt effekt. Tilhengerens plassering er også markert inn i skissen sett ovenfra.

I Figur 3 vises noen bilder fra måleoppsettet på Gråkallen.

Figur 3 Bilder av måleoppsettet på Gråkallen. Tilhengeren har påmontert metrologiloggeren på en stang bak. Fire mikrofoner ble plassert rundt vindturbinen, 2.4 meter over bakken, 4 meter fra vindturbinen. To batterikasser sto plassert på bakken under målingene og fungerte som elektrisk last for vindturbinen under målingene. Tunnelåpningen kan sees foran den røde bilen på bildet øverst til høyre.

2.2 Måleutstyr

Måleoppsettet besto av følgende utstyr:

Tabell 1 Liste over utstyr brukt under støymålingene på Gråkallen.

Hva	Antall	Beskrivelse
TurboMill vindturbin	1	
Batteripakke	2	2 batterier i hver boks. Fungerte som last under målingene.
Norsonic Nor121	2	Støyloggingsenheter, klasse 1, to kanaler på hver enhet.
Norsonic mikrofoner	4	½" mikrofoner med 90 mm vindhetter
Stativ	4	Stativ med minimum høyde 2.4 meter
Vaisala WXT520	1	Metrologiloggingsenhet
PC	1	Loggføring av metrologidata
Kalibrator	1	Brüel og Kjær, klasse 1 kalibrator
Tilhenger med låsbart lokk	1	
Diverse kabling		

2.3 Måleresultat

Under følger en presentasjon av resultatene fra kildeklassifiseringen på Gråkallen.

2.4 Regresjonsanalyse

Til hvert datasett er det gjort en regresjonsanalyse som baseres på følgende antakelser:

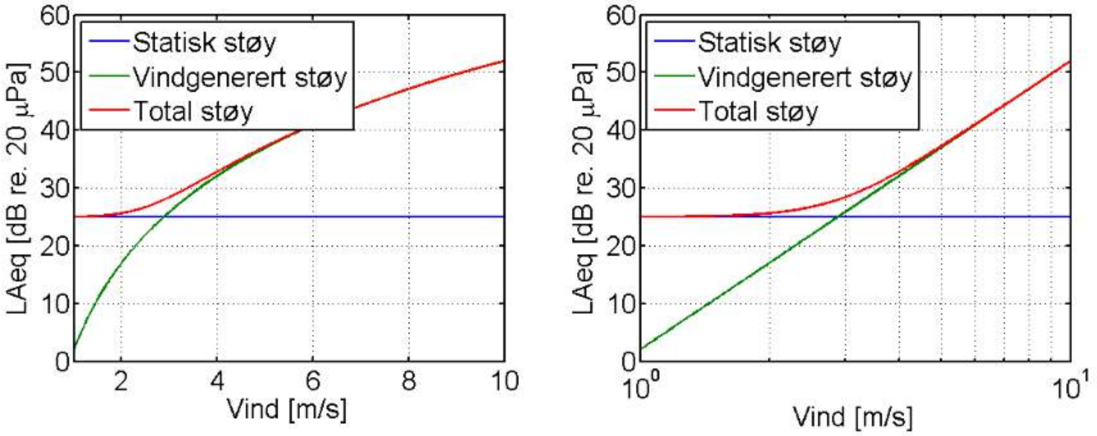
- Det er antatt at det eksisterer en nedre støygrense i målingene (statisk)
- Det antas at vindstøyen (både bakgrunnsstøy og fra vindturbinen) har en logaritmisk økning som funksjon av vind.

Dette kan beskrives med funksjonen

$$f(x) = 10\log_{10}\left(10^{\left(\frac{p1}{10}\right)} + 10^{\left(\frac{p2+10\log_{10}\left(x^{p3}\right)}{10}\right)}\right).$$

Kurvetilpasningen blir gjort ved at de tre parameterne *p1*, *p2* og *p3* blir endret. Minste kvadratiske feil blir brukt som tilpasningskriterium.

I Figur 4 er de to overnevnte punktene visualisert.



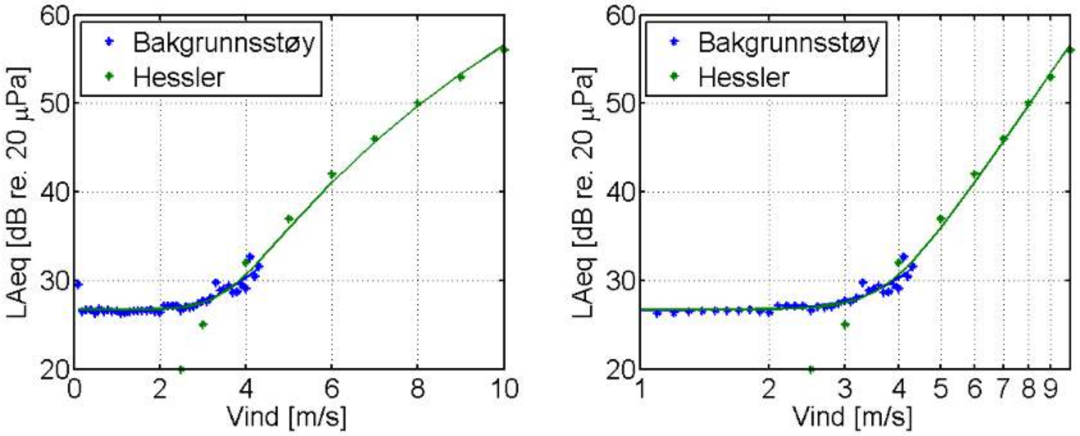
Figur 4 Illustrasjon av statisk støy (uavhengig av vind) og vindgenerert støy, sammen med summen av disse to. Eneste forskjell mellom venstre og høyre plot er x-aksen som er henholdsvis lineær og logaritmisk.

Det statiske støygulvet fra målingene stammer først og fremst fra ventilasjonsstøy fra tunnelåpningen ved siden av måleområdet (se Figur 3). I tillegg vil det også være et elektronisk støygulv i måleoppsettet som vil være uavhengig av vindstyrke.

2.5 Bakgrunnsstøymålinger

På slutten av måleperioden ble vindturbinen fjernet og vi gjorde opptak av ren bakgrunnsstøy. Dette ble gjort for å undersøke om det var nivåforskjell mellom målingene med og uten vindturbinen. Hvis nivåene med og uten vindturbin var like ville vi ikke kunne si noe om støyen generert av vindturbinen. Som vi allerede har vist var det forskjell mellom nivåene med og uten vindturbin.

I 2009 gjorde Hessler en studie av vindgenerert støy i vindhettene til mikrofoner [2]. Han testet blant annet den vindhetten vi benyttet under målingene, en Norsonic 90 mm vindhette. I Figur 5 kan Hesslers lab-måling av denne vindhetten sees sammen med bakgrunnsstøymålingene vi gjorde på Gråkallen. Hvis vi antar et statisk støygulv på omtrent 27 dBA, ser vi at tilpasningskurven passer veldig godt med Hesslers målinger. Dette gjør også at vi kan konstatere at det er vindhettestøy vi har målt når vinden har vært over 3 m/s.



Figur 5 Bakgrunnsstøymålingene sammen vindhettestøymålinger av en Norsonic 90 mm vindhette, gjort av Hessler i 2009 [2]. Eneste forskjell mellom venstre og høyre plot er x-aksen som er henholdsvis lineær og logaritmisk.

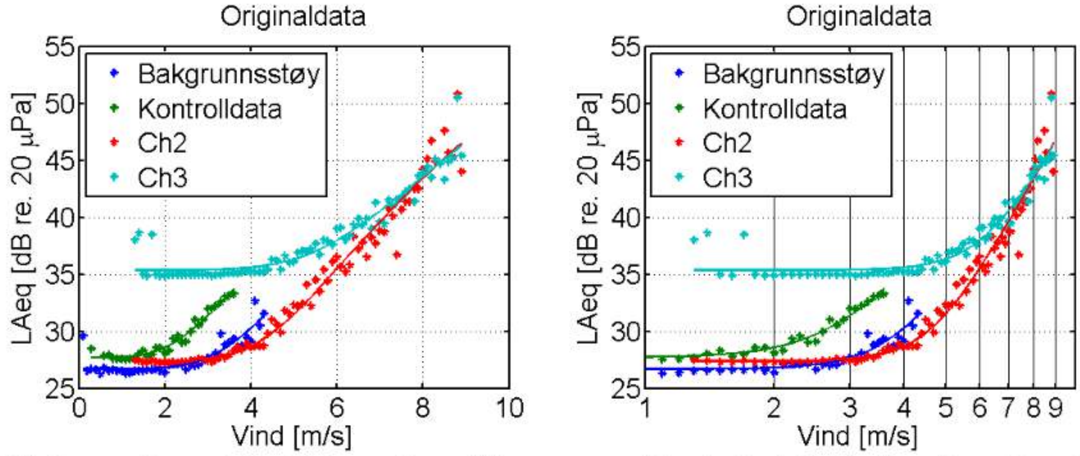
Samsvaret mellom Hessler vindhettestøy og våre målinger bekrefter at området vårt var stille og at oppsettet har fungert. Støygulvet på 27 dBA stammer fra ventilasjonsstøyen i tunnelen.

2.6 Originaldata

Målingene ble tatt opp ved hjelp av to Norsonic Nor121-enheter. Pga. tekniske problemer med disse enhetene ble de første måleresultatene vi gjorde usikre. Mot slutten av måleperioden fikk vi gjort kvalitetssikrede målinger, både med og uten vindturbinen. Problemet med disse målingene var at de ikke inneholdt vinddata over 4 m/s. De første dataene vi målte hadde, derimot, vindstyrker opp mot 9 m/s og vi ønsket derfor å få disse inkludert. Det ble derfor gjort en tilpasningsjobb, beskrevet under punkt 2.7.

I Figur 6 kan originaldataene sees – både bakgrunnsstøy, kontrolldata og de usikre målingene. Som man kan se har bakgrunnsstøydataene og kontrolldataene kun vindhastigheter opp til ca. 4 m/s. "Ch2" og "Ch3" er de usikre dataene som inneholder vindhastigheter opp til 9 m/s. Usikkerheten er at "Ch2" ser ut til å ha for lavt vindgenerert støynivå, mens "Ch3" ser ut til å ha både et unormalt høyt statisk støygulv, og et lavt vindgenerert støynivå.

Regresjonsanalysen av "Ch2" og "Ch3" viste at stigningstallet (*p3*) var tilnærmet lik (henholdsvis 6,8 og 6,7) for de to kanalene og vi valgte derfor å se bort fra "Ch3"-dataene i den videre signalbehandlingen. Dette på grunn av det unaturlig høye støygulvet i målingene som mest sannsynlig stammer fra elektronisk støy i dataloggeren.

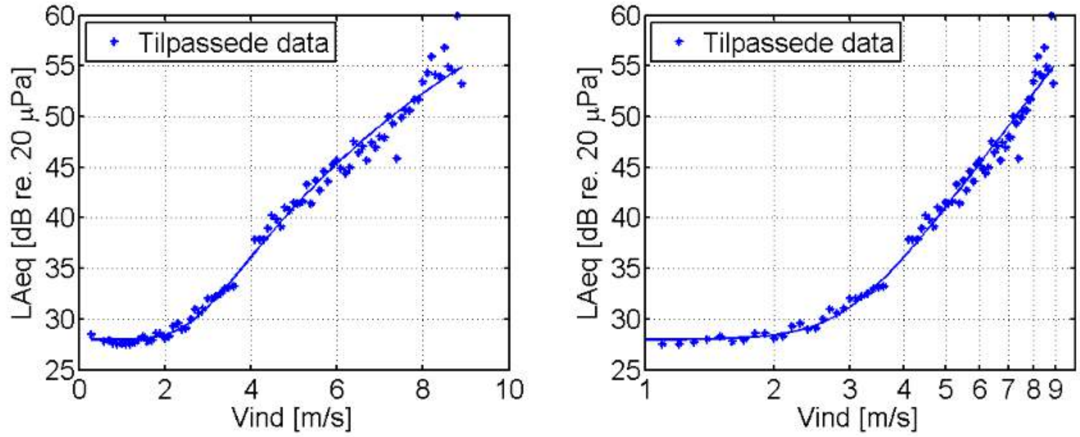


Figur 6 Plot som viser originaldataene fra målingene som ble gjort på Gråkallen. De usikre dataene er "Ch2" og "Ch3". Eneste forskjell mellom venstre og høyre plot er x-aksen som er henholdsvis lineær og logaritmisk.

Fra kontrolldataene og bakgrunnsstøydataene er det mulig å se at vindturbinen bidrar med en støykomponent til omgivelsene som overstiger bakgrunnsstøynivået. Forskjellen i nivå under 1 m/s kommer på grunn av ventilasjonsstøyen fra tunnelåpningen som lå rett ved siden av måleoppsettet. På grunn av avstandsforskjell fra tunnelåpningen til mikrofonene kan man se små nivåforskjeller i dette støygulvet mellom målingene.

2.7 Justerte data

For å kunne få med de usikre dataene i resultatet ble det gjort et forsøk på å justere disse til å passe med kontrolldataene. Ved å benytte kontrolldataene opp til 4 m/s og deretter benytte de usikre dataene for vindhastigheter over 4 m/s ble det gjort en regresjonsanalyse der RMS-feilen ble regnet ut. En justering på 9.2 dB ga minst RMS-feil, og tilpasningen kan sees i Figur 7.



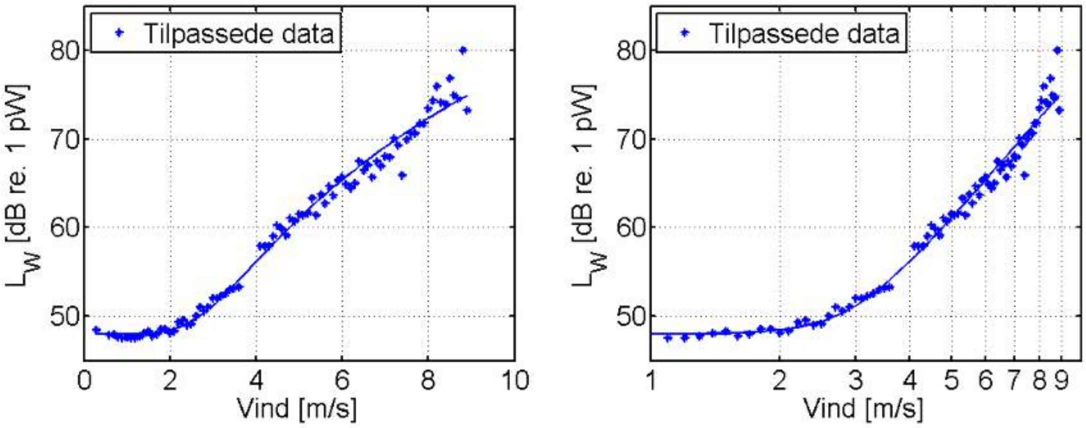
Figur 7 Plot som viser de tilpassede dataene. Eneste forskjell mellom venstre og høyre plot er x-aksen som er henholdsvis lineær og logaritmisk.

2.8 Utstrålt lydeffekt

Basert på de tilpassede dataene ble det beregnet en utstrålt effekt som funksjon av vind. Dette ble gjort ved hjelp av følgende ligning:

$$L_W = \overline{L_p} + 10\log_{10}\frac{S}{S_0},$$

der $\overline{L_p}$ er midlet lydtrykk over alle målemikrofonene, $S = 2\pi r^2$, der r er måleradiusen på 4 m, og S_0 er en referanseflate på 1 m^2. Dette gir en utstrålt effekt som kan sees i Figur 8.



Figur 8 Utstrålt effekt fra TurboMill som funksjon av vind. Eneste forskjell mellom venstre og høyre plot er x-aksen som er henholdsvis lineær og logaritmisk.

3 Påvirkning til omgivelsene

Retningslinje for behandling av støy i arealplanlegging (T-1442/2012 [3]) sier at industri med helkontinuerlig drift bør ikke overskride L_{den} = 55 dBA og L_{night} = 45 dBA. L_{den} er et døgnmiddel, mens L_{night} er et ekvivalentnivå for perioden mellom kl. 23-07. Kravet til støy om natten er strengere enn andre deler av døgnet og siden en vindturbin vil utstråle lyd uavhengig av tiden på døgnet, vil L_{night}-kravet være det aktuelle å benytte.

Vindturbiner blir generelt vurdert ut fra utstrålt effekt ved en vindhastighet på 8 m/s. Ved denne vindhastigheten er det funnet ut at vindturbiner støyer relativt mye, og forskjellen mellom støy fra vindturbin og bakgrunnsstøy er stor. Dermed er også sjenansen fra vindturbinene størst ved denne vindhastigheten. Ved denne vindhastigheten har vi beregnet en utstrålt effekt på 72,3 dB re. 1 pW.

Når man vet utstrålt effekt kan man finne lydtrykk i en gitt avstand ved hjelp av uttrykket:

$$L_p(r) = L_W + 10\log_{10} N - 10\log_{10}(4\pi r^2) = L_W + 10\log_{10} N - 20\log_{10} r - 11,$$

der L_W er utstrålt effekt, N er antall moduler og r er avstanden man ønsker å beregne lydtrykk for. Dette uttrykket vil gjelde for vindturbiner plassert i høyden, f.eks. på et tak. Hvis man plasserer vindturbinene på bakken vil sfæren lyden utbres i reduseres fra $4\pi r^2$ til $2\pi r^2$ (halvsfære). Dette gir et tillegg på 3 dB på lydtrykket i et gitt punkt. Figur 9 viser plot av lydtrykksnivå som funksjon av avstand fra tre kildeoppsett; 4 moduler, 8 moduler og 16 moduler. En dobling i antall moduler bidrar også til 3 dB økning i lydtrykket.

Uttrykket over kan vi snu litt om på og finne hvor langt unna man må for å komme under kravet på 45 dBA. Vi får da:

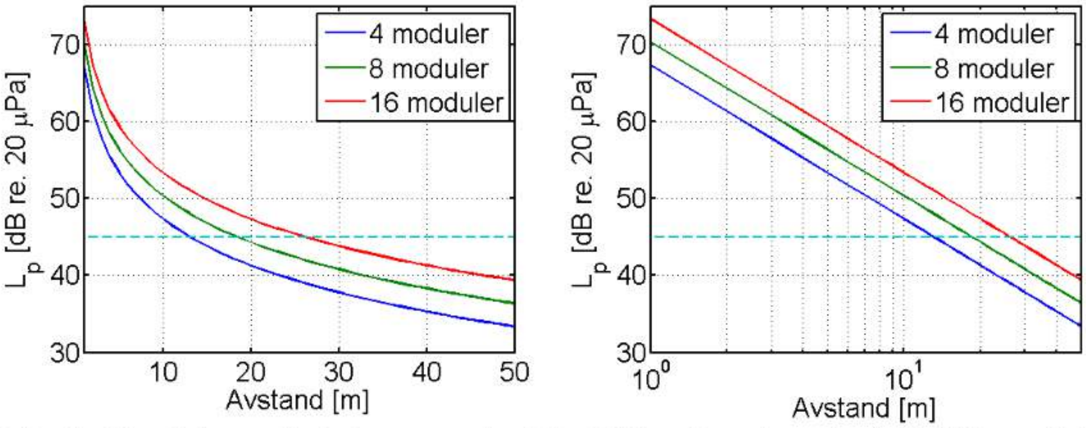
$$\mathrm{d} = 10^{\frac{L_W + 10\log_{10} N - 11 - 45}{20}}.$$

Hvis vi antar at man benytter åtte TurboMill-moduler (som på Postgirobygget) på et tak får vi en avstand på:

$$\mathrm{d} = 10^{\frac{72{,}3 + 10\log_{10} 8 - 56}{20}} = 18{,}5\ m.$$

Dersom disse åtte vindturbinene hadde blitt plassert på bakken ville avstanden øke til

$$\mathrm{d} = 10^{\frac{72{,}3 + 10\log_{10} 8 - 53}{20}} = 26{,}1\ m.$$



Figur 9 Lydtrykksnivå som funksjon av avstand fra kilden. L_{night}-kravet på 45 dBA er stiplet inn og viser hvilken avstand hvert av oppsettene går under kravet. Vindhastigheten som er brukt til simuleringene er 8 m/s. Eneste forskjell mellom venstre og høyre plot er x-aksen som er henholdsvis lineær og logaritmisk.

3.1 Kommentarer

Resultatene over beskriver et "verst tenkelig" oppsett. Dette er gjort med hensikt på grunn av usikkerhet i målingene og for å gi en konservativ vurdering av støy generert av vindturbinene.

I de aller fleste realistiske oppsettene vil man ikke kunne se alle vindturbinene for eksempel fordi noen av turbinene vil være trukket inn mot midten av et tak. Dette vil føre til en støyskjermende effekt som vil redusere nivået til en mottaker. Man vil også, enkelt, kunne skjerme for en del av støyen hvis dette skulle være nødvendig.

Vi har også sett bort fra eventuelle bidrag fra bakgrunnsstøy på grunn av manglende data ved 8 m/s vindhastighet. Et eventuelt bidrag fra bakgrunnsstøy skal også trekkes fra utstrålt effekt.

4 Befaring på installasjon

En befaring på installasjonen på Biskop Gundersens gate 14A ble gjennomført 27. november 2012. Vindturbinene var på dette tidspunktet stoppet med tau for å hindre skade på modulene under kraftig vind. Entra ventet på en "brake unit" som skulle hindre turbinene fra å gå for raskt rundt.

Vindhastigheten på taket var, anslagsvis, 5-6 m/s, og det var lett nedbør (sludd) i lufta.

På grunn av mye bakgrunnsstøy ble det bestemt å ikke løsne vindturbinene, men i stedet måle nivået på bakgrunnsstøyen. Nivået ble målt over en 10 sekunders periode ved hjelp av en Norsonic Nor131 lydmåler med 70 mm vindhette, på fire punkt rundt vindturbinene. Nivåene kan sees, sammen med det midlede nivået over alle punktene, i Tabell 2.

Tabell 2 Bakgrunnsstøynivå rundt vindturbinene på Biskop Gundersens gate 14A i Oslo.

Beskrivelse	**Nivå (dBA)**
Punkt 1	60.7
Punkt 2	64.3
Punkt 3	68.7
Punkt 4	63.6
Midlet nivå	65.3

Bakgrunnsstøyen besto av lyd fra ventilasjonsanlegg, vindstøy fra flaggstenger, ledninger og andre installasjoner på taket.

Befaringen avslørte ingen unormale støykilder som følge av montering av vindturbinene.

5 Oppsummering

Oppdraget var å beregne støypåvirkning til omgivelsene fra vindturbiner av type TurboMill. For å gjøre dette gjennomførte vi en kildeklassifisering av én TurboMill-modul for å vite hvilken utstrålt effekt disse har. Denne undersøkelsen viste at utstrålt effekt ligger på et så lavt nivå at det ikke kommer til å medføre negativ støypåvirkning til omgivelsene. Allerede på en avstand på omtrent 15-25 meter fra vindturbinene, avhengig av antall turbiner og plassering, vil støynivåene være under L_{night}-kravet på 45 dBA.

Siden Postgirobygget i Oslo er 112 meter høyt vil støyen som når bakken være langt under L_{night}-kravet og ikke ha noen negativ effekt på omgivelsene.

I Trondheim, på Brattørkaia 17B, er ikke høyden kjent, men siden bygningen har 8 etasjer, antas den å være over 30 meter. Det betyr at også her vil støyen som når bakken være under L_{night}-kravet og ikke ha noen negativ effekt på omgivelsene.

Befaringen på installasjonen i Oslo viste også at med en vindhastighet rundt 5 m/s er bakgrunnsstøyen over 60 dBA på taket. Dette betyr at bakgrunnsstøyene vil overgå støyen fra vindturbinene og føre til maskering. Dette forsterker konklusjonen med at vindturbinene ikke vil ha noen negativ konsekvens på omgivelsene.

Referanseliste

[1] NORDTEST Industrial plants: Noise emission, NT ACOU 080, Approved 1991-02.

[2] D. M. Hessler, 2009, *Wind Tunnel testing of Microphone Windscreen Performance Applied to Field Measurements of Wind Turbines*, Third International Meeting on Wind Turbine Noise, Aalborg, Denmark.

[3] T-1442, 2012, *Retningslinje for behandling av støy i arealplanlegging*, http://www.regjeringen.no/pages/37952459/T-1442_2012.pdf

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May 2012

WindStream
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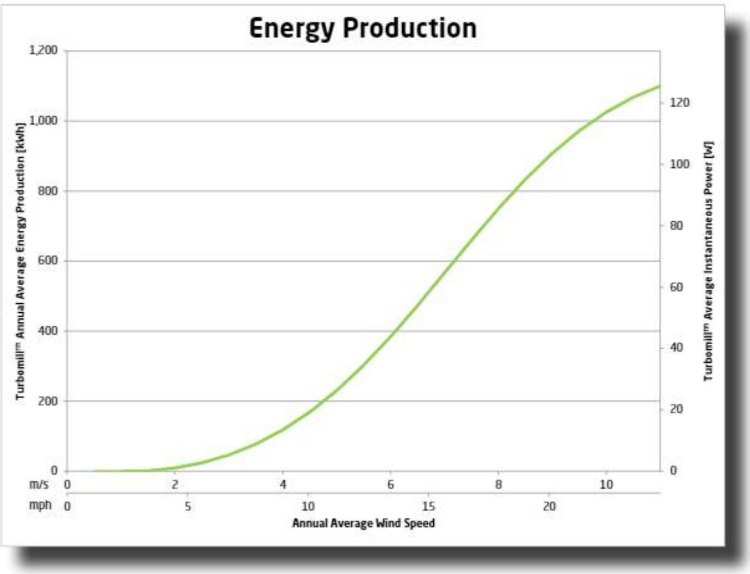
Installation Benefits

- Unique form factor, easily mounted to any building
- No complicated masts, guy wires, or towers
- Avoids engineering and permitting complexities
- Suitable for simple ballasted installation that avoids roof penetration
- Visually engaging design integrates with existing building architecture, custom colors available
- Durable construction, engineered for any environment
- Environmentally friendly, virtually silent

Technical Specifications

Energy Potential (Per Unit)	230 kWh per year @ 5 m/s average wind speed
Rated Power Output	143 W @ 11 m/s
Maximum Power Output	500 W @ 17 m/s
Maximum Voltage	57 DC
Maximum Current	30 Amps
Rotor Diameter	12.99 in | 0.33 m
Cut-In Wind Speed	4.5 mph | 2 m/s
Cut-Out Wind Speed	38.03 mph | 18.5 m/s
Swept Area	1,519 in^2 | 0.980 m^2
TurboMill® Dimensions	51.18 in x 51.18 in x 25.197in
Weight	82.3 lbs | 37.33 kg
Turbine Material	Galvanized G-90 Steel
Corrosion Prevention	PPG Spectracron® 360 2K
Electrical Connection	On-Board Battery Charge Controller Grid-Tied Inverter (Optional)
Generator	Brushless, Permanent Magnet Generator
Design Life	20 Years



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Building integrated vertical wind turbines

EXPERIENCES FROM THE ROOF OF BISKOP GUNNERUS GATE 14 IN OSLO

This report describes results of the installation of vertical axis wind turbines on the top of 'Biskop Gunnerus gate 14' in Oslo. Measurements of wind, electricity production and noise were taken and correlated. The results show a good match. Technical challenges during the whole project are described and the strengths and weaknesses of the wind turbines are discussed. The conclusions highlight the need for further work that is needed to harvest the potential of wind power integrated into the built environment.

SINTEF akademisk forlag