

Building augmented wind turbines – BAWT

INTEGRATED SOLUTIONS AND TECHNOLOGIES OF SMALL WIND TURBINES



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Abstract

The aim of the project is to develop new knowledge, integrated solutions, and technologies of small/micro wind turbines. Financed by the Norwegian State Housing Bank (Husbanken) the project tries to analyse possibilities for the increased use of small/micro wind turbines and starts with a review of wind turbine technology and international projects where wind turbines were installed and - moreover – integrated into the building design. Available documentation was reviewed with respect to building design, technologies applied, and resulting energy performance, cost and other significant experiences. Further should the project develop more knowledge of the acceptance of integrated solutions and review the barriers and potential for such wind turbine technology in Norway. These investigations included measurements, interviews, and audits. Also, energy simulations were carried out and compared/calibrated to measured data. The results show that effect of location is very important, together with turbine type and size. The wind conditions can be influenced by designers and planners by taking urban and building design in to account and specifically focusing on the parameters axis height, surrounding topography and wind channeling effects.

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1 Introduction

1.1 Aim

The aim of the project is to develop new knowledge, integrated solutions, and technologies of small/micro wind turbines. Financed by the Norwegian State Housing Bank (Husbanken) the project tries to analyse possibilities for the increased use of small/micro wind turbines and starts with a review of wind turbine technology and international projects where wind turbines were installed and – moreover – integrated into the building design. Available documentation was reviewed with respect to building design, technologies applied, and resulting energy performance, cost and other significant experiences. Further should the project develop more knowledge of the acceptance of integrated solutions of wind turbine technology in Norway and finally it should review the barriers and potential for such wind turbine technology. Where needed, additional investigations were carried out in order to establish a thorough understanding of the performance and challenges to be faced. These investigations included measurements, interviews, and audits. Also, energy simulations were carried out and compared/calibrated to measured data.

1.2 Background

A market with great potential for small wind turbines is in grid-connected applications for residential, industrial or even, lately, urban environments. The so-called distributed wind applications are projected for rapid market growth in response to continuing energy price increases and increased demand for on-site power generation. However, in order for distributed wind to reach its mainstream market potential, the industry must overcome several hurdles, primarily in system costs, quality of design, grid interconnection, and installation restrictions.

Presently, the major share of development of this market is in the US, UK and Canada in parallel with new trends in the development of distributed generation systems. This emerging market provides a new impulse to the development of small wind turbine technology.

Wind power can also be used to generate electricity in an urban environment. This trend has mainly been seen in Europe, where the integration of small/micro wind turbines in the built environment is being actively discussed. New wind turbines are under development for this application, which is looking mainly for quiet and efficient devices under turbulent and skewed wind flow.

As well as the installation of wind turbines around and on buildings, there is also interest in **building integrated** wind turbines where the technology is integrated into the building design, and even **building-augmented** wind turbines, where the turbine is part of the building structure or façade. The design of the building in this case are augmented in order to get the optimum out of the wind power. For these applications, due attention should be paid to the acceptance of building owners and neighbors prior to installation.

1.3 Objectives

The overall aim of the project is to develop new knowledge, integrated solutions, and technologies of small/micro wind turbines. More specifically, this should result in:

- *Establish an overview of current best practice of building augmented wind turbines.*
- *Develop knowledge of social acceptance of building augmented wind turbines.*
- *Develop knowledge of barriers and potential of building augmented wind turbines.*

1.4 Scope of work

In order to reach the goals in the project, the work was divided into 4 tasks:

Task 1 - Chapter 2

The first task that was carried out, was the investigation of a number of existing state-of-the-art building augmented wind turbines realised in Norway and abroad. Available documentation was studied with respect to building design, technologies applied, and resulting energy performance, cost and other significant experiences. Where needed, additional investigations were carried out in order to establish a thorough understanding of the performance and challenges to be faced. These investigations included measurements and energy simulations which were compared/calibrated to measured data.

Task 2 – Chapter 3

Based on wind data for three different locations (**Oslo, Trondheim and Tromsø**) a parametric study was conducted in order to evaluate the influence of influencing parameters wind turbine type, axis height, turbine area, surrounding topography, and wind channeling effect. The results will be helpful for designers and planners that wish to install small/micro wind turbines in understanding better the influence of those parameters on wind energy potential.

Task 3 – Chapter 4

The BIWT technologies was analyzed in a broad view including architectural integration, aesthetics, functional demands, technical issues and economic issues. Therefore, user acceptance of building augmented wind turbines in residential areas was studied. For this, two types of **questionnaires** were used; one questionnaire was web-based and spread to a large group of building owners; the other questionnaire involved in-depth interviews with a smaller number of building owners in Stokkøya. The results from both questionnaires formed the basis of a comprehensive analysis of the results.

Task 4 – Chapter 5

In order to integrate wind power efficiently at higher penetration levels, changes to the operating methods of various parts of the power system are required, such as generators and transmission systems. Moreover, active management at the design side of the power system can be used to facilitate **wind power integration**. Wind power, with its variable output characteristics, affects other generators in the system. As well as reducing their required output, wind power also requires other power plants in the system to be scheduled differently in order to support the stability of the electricity grid.

1.5 Further reading

Based on the findings a paper for CISBAT, an International conference which was held in Lausanne in September 2015 (Haase and Skeie, 2015) was written and presented. In addition, there are plans to publish another paper with a summary of findings at appropriate conferences. Especially the results from the user acceptance analysis will be interesting for the research community.

2 Task 1: State-of-the-art

2.1 Overview

In the initial phase of the project, a number of existing state of the art building augmented wind turbines realised in Norway and abroad were studied. The following work was considered:

- **Definition and explanation of relevant terms used:** wind turbines technology was reviewed and the most important terms used are explained.
- **Wind and energy:** this section reviews what we know about wind velocities especially in the built environment and what we do not know (and what we should know);
- **The role of building design for building augmented wind turbines:** wind velocities and power coefficients are the most important factors that determine the effectiveness of wind turbines. Building design can have a crucial role in successful application (and in failure);
- **Experiences from measurements:** wind velocity and wind direction was measured over a period of 13 months on top of the roof of a high-rise building in Oslo. Results of wind velocity measurements and conclusions are presented.

2.2 Definitions

2.2.1 Terms and types

A wind turbine is a popular name for a device that converts kinetic energy from the wind into electrical power. Technically, there is no turbine used in the design, but the term appears to have migrated from parallel hydroelectric technology (rotary propeller).

*The correct description for this type of machine would be **aerofoil-powered generator** (wiki: https://en.wikipedia.org/wiki/Wind_turbine).*

Usually, the term Large Wind Turbine (**LWT**) refers to the ones rated above 100kW, then Small Wind Turbines (**SWT**) are between 10kW and 100kW and finally Micro Wind Turbines (**MWT**) are below 10kW (Dutton, Halliday and Blanch, 2005).

In the context of this document, building integrated wind turbines are wind turbines that are integrated into the building. Typically, there are different levels of integration to distinguish (see chapter 2.1.2 for more explanation).

The most integrated wind turbines are so-called augmented wind turbines that are defined as turbines that are specially designed for built environment, and can be located on buildings or on the ground next to buildings. This implies that the turbine has been adapted for the wind regime (i.e. wind velocity profiles and directions) in the built environment and can, in theory at least, resist wind gusts and turbulences. In addition, it implies that the shape and size of the turbine have been designed to visually integrate with the surrounding buildings. The capacity of these turbines is generally between 1 and 20 kW. These wind turbines is also referred to as “urban wind turbines” (**UWT**) (Cace, et al., 2007).

The following types of wind turbines and fields of building related wind turbine applications can be distinguished:

1. rotor types with the following sub-division
 - Horizontal axis wind turbine (**HAWT**)
 - Vertical axis wind turbine (**VAWT**)
2. Building mounted wind turbine (**BMWT**)

3. Building integrated wind turbine (**BIWT**)
4. Building augmented wind turbine (**BAWT**)

Building mounted wind turbines (BMWT) are physically linked to the structure of the building. This way, the buildings is effectively used as a tower to place the turbine in a desirable wind flow, and its structure must be able to support the turbine both in terms of loads and within noise and vibration constraints. They are capable of functioning close to buildings and exploiting any augmentation that these might cause to the local wind. This type of wind turbines are typically mounted on the roof.

Building integrated wind turbines (BIWT) should be included somehow into the building design. Wind turbines can be integrated in different ways. They can be integrated from the constructional point of view, from the architectural point of view and even from an electrical or energy point of view.

Building augmented wind turbines (BAWT) are those integrated in such a way that the building itself deliberately alters and augments the flow into the turbine. This requires a more specific design of the building for that purpose.

In the following sections the different types are explained in more detail and with help of showing some built examples.

2.2.2 Horizontal and vertical axis wind turbines

Horizontal-axis wind turbines (**HAWT**) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator (Illustrated history of wind power development, <http://www.telosnet.com/wind/early.html>).

Vertical-axis wind turbines (or **VAWTs**) have the main rotor shaft arranged vertically. One advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective, which is an advantage on a site where the wind direction is highly variable. It is also an advantage when the turbine is integrated into a building because it is inherently less steerable. Also, the generator and gearbox can be placed near the ground, using a direct drive from the rotor assembly to the ground-based gearbox, improving accessibility for maintenance.

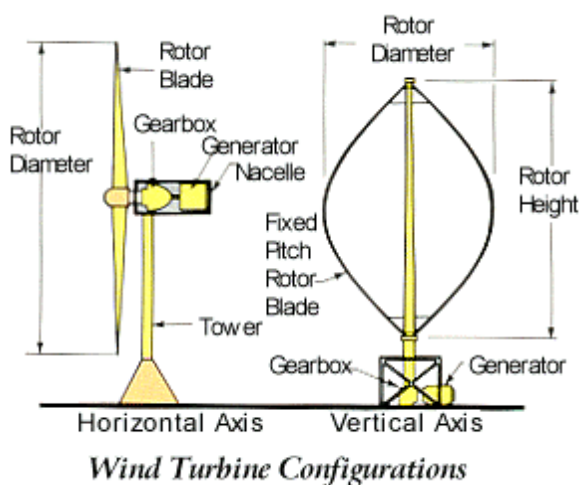


Figure 1 – Typical configurations for horizontal and vertical axis wind turbines (www.daviddarling.info)

2.2.3 Building mounted wind turbines

Different types

Many different types of small wind turbines are available on the market. 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).

Building mounted wind turbine with horizontal axis rotor type

Figure 2 illustrates different examples for building mounted wind turbines. The horizontal axis rotor type is usually mounted on a mast and then on the roof structure. Vibration issues must be handled. The position on top of the building is often chosen to minimize visual impacts. Ideally, wind availability measurements should be conducted prior to construction.



Figure 2 – Roof mounted wind turbines

Building mounted wind turbine with vertical axis rotor type

Figure 3 illustrates different examples for building mounted wind turbines with vertical axis rotor type. It is often mounted on a sub-structure and then placed on the roof structure.



Figure 3 – Vertical axis wind turbines, roof mounted

2.2.4 Building integrated wind turbines

The word "integrated"

Even if the installation of wind turbines around and on buildings is of interest, there is also interest in "building-integrated" wind turbines, where the turbine is part of the building structure or façade. Small vertical wind turbines are more easily to integrate than large scale wind turbines. However, the understanding of building integrated wind turbines is not coherent. This is mainly due to the ambiguous use of "integrated". Many wind turbines that can be found in the built environment claim to be "building integrated". And indeed can wind turbines be integrated in different ways. They can be integrated from the constructional point of view, from the architectural point of view and even from an electrical or energy point of view. "Building integration" can be used when systems are integrated into the construction and also design of a building (Bachman, 2003).

Structural integration of wind turbines provides many challenges. A mast or support structure for the wind turbine is normally needed in addition to the primary building envelope. Integration requires the use of one element for different purposes. An important aspect is the positioning of the BIWT in the building. Vibration and noise transmission are potential issues. Test measurements 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 structural support system and connection to the building structure. Noise measurements undertaken on a small vertical axis wind turbine showed little noise

Electrical integration of small wind systems and its hybrid applications can play an increasingly important role in expected future ideal distributed networks. 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 stabilization of the power grid. 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 m² 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.

Architectural integration is even more difficult to evaluate. If **BIWT** add to the overall expression of a building has not been subject of detailed studies yet. Bachman (2003) argues to separate into hardware and software; the first refers to the integration among building systems (physical, visual and performance integration) while the second refers to integration in the design process (unifying art and science, team approach and the accumulated wisdom of architecture).

Poerschke (2011) developed some guidelines for the integration of wind turbines in architecture and the built environment and defined 6 main strategies of wind turbine integration used in the design studio (Poerschke, 2011).

In **Building integrated Photovoltaics (BIPV)** the following definition is used:

The acronym BiPV refers to systems and concepts in which the photovoltaic element takes, in addition to the function of producing electricity, the role of a building element. In recent years, the integration of modules in architecture is strongly evolving. New BiPV products, with their sizes and characteristics, are able to fully replace some building components. By BiPV element we mean a building component used as part of the building envelope (covering element of the roof, facade cladding, glass surfaces, etc.), sun protection devices (shading), architectural elements or "accessories" (such as canopies, balcony parapets, etc.) and any other architectural element that is necessary for the proper functioning of the building (e.g. visual and acoustic shielding). www.bipv.ch

Building integrated wind turbine with horizontal axis wind turbine as type

This type of building integration can be found in some larger building projects. *Figure 4* shows a good example where three horizontal axis wind turbines were integrated into the roof structure.



Figure 4 – Building integrated wind turbines with horizontal axis (Strata SE 1, London)

Building integrated wind turbine with horizontal axis wind turbine as type

Figure 5 shows a good example of wind turbines integrated into the facade of a building. It is located in San Francisco, CA, USA and was completed in 2012. It is a 13 floor administration building designed by US-based architectural office KMD, Stevens, JV.



Figure 5 – Building integrated wind turbines with vertical axis (Public utility commission HQ, San Francisco)

2.2.5 Building augmented wind turbine

Part of the building design

Even if the installation of wind turbines integrated into buildings is of interest, there is also interest in "building-augmented" wind turbines, where the wind turbine is part of the building design. The design of the building in this case are augmented in order to get the optimum out of the wind power. For these applications, due attention to the optimum design with regard to the available wind velocities is needed. Not all of the examples can prove a change of the design due to expected wind velocities. The augmentation of the building design is normally not documented.

Building augmented wind turbine with horizontal axis rotor type

Figure 6 shows an example of a building augmented wind turbine project with horizontal axis rotor type. The two towers are linked via three skybridges (see *Figure 6* on the right), each holding a 225kW wind turbine. Each of these turbines measure 29 m in diameter, and is aligned north, which is the direction from which air from the Persian Gulf blows in. The building design was augmented to provide a channeling effect and thus to enhance wind velocities. The sail-shaped buildings on either side are designed to funnel wind through the gap to provide accelerated wind passing through the turbines. This was confirmed by wind tunnel tests, which showed that the buildings create an S-shaped flow, ensuring that any wind coming within a 45° angle to either side of the central axis will create a wind stream that remains perpendicular to the turbines (results from some studies are shown in *Figure 13*). This significantly increases their potential to generate electricity.



Figure 6 – Building augmented wind turbine, horizontal axis (World Trade Center, Bahrain). For more explanation see also Figure 13).

Building augmented wind turbine with vertical axis rotor type

One recent project that was finished in 2012 is the Greenway Self Park, a partially self-powered, 11-story parking garage in downtown Chicago designed by US based architectural firm HOK. The building's dozen vertical-axis wind turbines are stacked in two double-helical columns along the southwest corner. This is a corner of the building where highest wind speeds can be expected. In addition is the design of the building augmented by opening and exposing the corner. Detailed wind pattern analysis could however not be found.

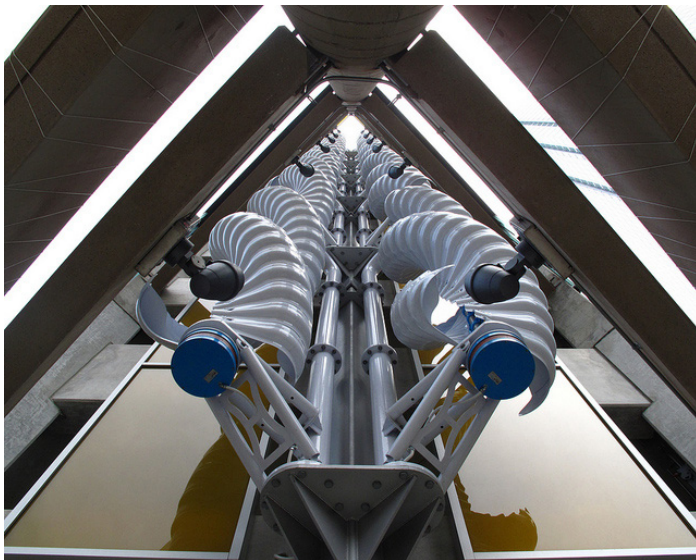


Figure 7 – Building augmented wind turbine (vertical axis) (Greenway Self Park, Chicago, USA)

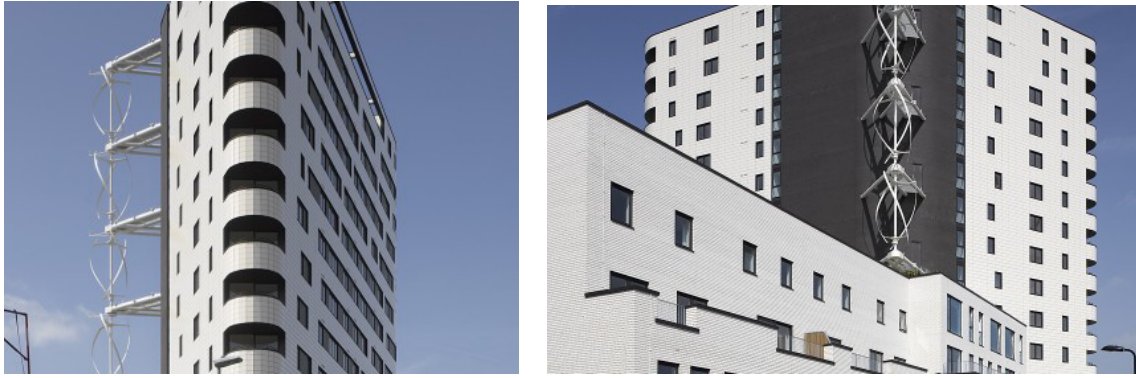


Figure 8 – Building augmented wind turbine (vertical axis) (Kinetica, Dalston, London)

Figure 8 shows another building augmented wind turbine example from Dalston, London, UK. This mixed-use (residential, offices) building with 14 floors was designed by London-based Waugh Thistleton and provides 4 vertical axis wind turbines (Quiet Revolution).



Figure 9 – Building augmented wind turbine (vertical axis) (Pearl River Tower, Guangzhou, China). For more explanation see also Figure 12.

Figure 9 shows another example of building augmented vertical axis wind turbine. The Pearl River Tower, Guangzhou, China, was completed in 2010, has 71 floors and was designed by SOM. The tower's aerodynamic form was developed through a careful understanding of solar and wind patterns around the site. The design optimizes the solar path and utilizes the sun to the building's advantage. The tower's sculpted body directs wind to a pair of openings at the mechanical floors, where turbines generate energy for the building (see *Figure 9* on the right and middle).

2.3 Wind and energy

2.3.1 Overview

This section reviews what is known about wind velocities especially in the built environment and what is not known (and what should be known). It starts with a review of wind energy theory, continues with a description of the role of the building and the rotor design and finishes with a summary of the experiences from measurements.

2.3.2 Wind energy 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 et al., 2006; Dutton, Halliday and Blanch, 2005; Mertens, 2006). Wind turbines aim to convert the power of the wind into electricity. In order to be able to estimate energy production some physical laws are reviewed.

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

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

with

- P = power of the wind (W)
- ρ = density (kg/m³)
- A = area (rotor cover) (m²)
- 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 and vice versa. If the actual wind velocity at a site is 10% higher than predicted, the performance is increased by 27%. A doubling of the wind velocity results in 8-fold performance.

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. The power coefficient can be determined with the following equation:

$$E_{el} = P_{wind} \times c_p \times 8760h \quad (\text{eq. 2})$$

with

- E_{el} = electricity production (kWh)
- P_{wind} = power of wind (W)
- 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%,

In order to evaluate wind turbines it is useful to compare the theoretical electricity production with 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.

Especially interesting is the correlation between wind velocities and direction between measurements, e.g. on the top of a building and at weather stations nearby. For being able to do this, the wind velocity and direction measurements can be calculated with the following formula:

$$v_{calc,t} = v_{station,t} \times z_t \times \left(\frac{h_{roof}}{h_{station}} \right)^\alpha \quad (\text{eq. 3})$$

with

- $v_{station,i}$ = wind velocity at weather station (hourly data) (m/s)
- $h_{station}$ = height of weather station (m)
- h_{roof} = height of installed wind turbines (m)
- $z_{1,2}$ = ratio of terrain factors ground roughness (from Table 3) (-)
- α = surrounding terrain roughness factor (e.g. from Table 3) (-)

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

$$P_{theo,t} = \frac{1}{2} \times v_{calc,t}^3 \times \rho \times A \quad (\text{eq. 4})$$

with

- A = rotor area (m²)
- ρ = density of air (assumed to be constant) = 1.25 kg/m³. Air density kept constant even though it depends on height as well as temperature
- $v_{calc,i}$ = calculated wind velocity (from eq. 3) (m/s)

Energy production based on wind velocity can be calculated with:

$$E_{theo,t} = \int_1^n P_{theo,t} \times \Delta t \quad (\text{eq. 5})$$

with

- $P_{theo,i}$ = theoretical wind power (from eq. 4)
- Δt = various time periods

The measurement results for wind velocity and power were compared and used to calculate the power coefficient (which are often provided by the producer).

$$c_p = \frac{P_{mea}}{P_{theo,m}} \quad (\text{eq. 6})$$

with

- P_{mea} = measured power output
- $P_{theo,m}$ = theoretical electric power with measured wind velocity (from eq. 4)

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

$$E_{calc,t} = c_p \times E_{theo,t} \quad (\text{eq. 7})$$

with

- c_p = power coefficient from (eq.6)
- $E_{theo,i}$ = theoretical electricity production (from eq. 5)

2.3.3 Wind velocity in the urban context

Strategy to understand the built-environment wind resource

The exploitation of the wind resources in urban areas is a recent idea. Urban wind turbines mounted on buildings are within the surface roughness layer, which extends above surface elements to at least 1–3 times their height. The roughness of this environment causes turbulence in the wind, thus reducing the energy production of many commonly used small wind turbines. However, studies on wind movement around obstacles such as buildings have shown that wind also accelerates when getting round them. The angle of incidence on a turbine can also increase its electricity production (Walker, 2011).

More detailed research is needed to evaluate wind pattern around groups of buildings (urban). Smith et al. (2012) came up with the following strategy to develop understanding of the built-environment wind resource (Smith et al., 2012).

The mean wind velocity can be determined by

$$\bar{V} = \frac{1}{T} \int_{t_0-T/2}^{t_0+T/2} V_t dt \quad (\text{eq. 8})$$

with

V_t = instantaneous wind velocity at time t

\bar{V} = mean velocity averaged over time interval T , centered on t_0

T = time interval, centered on t_0

The gustiness of turbulence is defined as

$$\sigma_v^2 = \frac{1}{T} \int_{t_0-T/2}^{t_0+T/2} (V_t - \bar{V})^2 dt \quad (\text{eq. 9})$$

with

σ_v = standard deviation or root-mean-square value of deviations of the instantaneous velocity from the mean

The relative gustiness or intensity of turbulence is defined as

$$I_v = \frac{\sigma_v}{\bar{V}} \quad (\text{eq. 10})$$

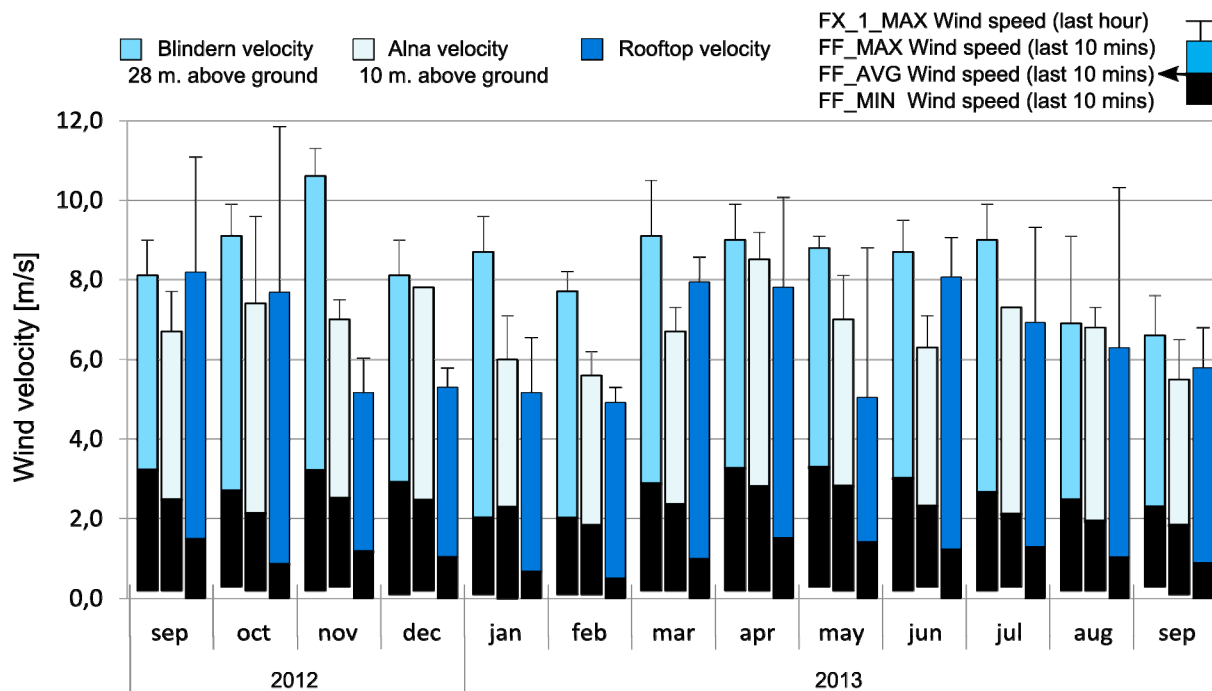


Figure 10 – Monthly wind velocities of different measurement stations (Haase and Skeie, 2015)

Figure 10 shows the average wind velocities for different measurement stations (in black) and maximum wind gusts (FX_1 and FF_MAX). This illustrates the dynamics of wind velocities.

The distribution of wind velocities in the atmosphere follows closely the Gaussian Normal distribution so that mean velocity \bar{V} and standard deviation σ_v are sufficient to describe statistically the variations in wind velocities over time interval T and thus the structure of the flow within the boundary layer.

Influence of height and terrain

The forces that define the flow pattern in the lower part of the atmosphere are:

- The forces of the pressure systems
- The Coriolis forces (related to rotation of earth)
- The frictional resistance determined by the rough boundary of the earth's surface
- Buoyancy forces related to vertical temperature gradients
- Viscous forces

In large scale systems only the first three types of forces play a significant role in determining the flow pattern. In the lower part of the atmosphere (below 500m) the influence of ground roughness and surface friction is important.

When a phenomenon involves a number of variables, such as length, velocity, density, viscosity, pressure etc. it is not necessary to discuss the effect of each variable. It is instead possible to formulate a relation between sets of dimensionless groups of variables (Aynsley et al., 1977).

It has been found convenient to express the scaling force ratios in relation to the inertia force which form the basis for commonly used dimensionless coefficients as shown in

Table 1.

Table 1: Some dimensionless coefficients used in aerodynamics to simplify data presentation (Aynsley et al., 1977)

1.	<u>pressure force</u> inertia force	$\frac{\rho A}{Ma} = \frac{\rho L^2}{\rho L^2 V^2}$
	pressure coefficient	$c_p = \frac{\rho}{\frac{1}{2} \rho V^2}$
	Lift coefficient	$c_L = \frac{Lift}{\frac{1}{2} \rho V^2}$
	drag coefficient	$c_D = \frac{Drag}{\frac{1}{2} \rho V^2 A}$
	moment coefficient	$c_M = \frac{Moment}{\frac{1}{2} \rho V^2 LA}$
2.	<u>Inertia force</u> Viscous force	$\frac{Ma}{\tau A} = \frac{Ma}{\mu \left(\frac{dV}{dy}\right) A} = \frac{\rho L^2 V^2}{\mu \left(\frac{V}{L}\right) L^2}$
	Reynolds number	$Re = \frac{\rho V L}{\mu}$
3.	<u>Inertia force</u> gravity force	$\frac{Ma}{Mg} = \frac{\rho L^2 V^2}{\rho L^3 g}$
	Froude number	$F = \frac{V}{(Lg)^{\frac{1}{2}}}$
4.	<u>Inertia force</u> elastic force	$\frac{Ma}{KA} = \frac{\rho L^2 V^2}{KL^2}$
	Stiffness number	$= \frac{\rho V^2}{E} \text{ or } \frac{\rho V^2}{E}$
	Mach number	$M = \frac{V}{(K/\rho)^{\frac{1}{2}}} = \frac{V}{C}$

where

M = mass

A = area

a = acceleration

g = gravity

L = length

V = velocity

ρ = density (kg/m³).

K = coefficient

μ = dynamic viscosity (Pa·s or N·s/m² or kg/(m·s))

ν = kinematic viscosity ($\nu = \mu/\rho$) (m²/s)

The boundary layer

The boundary layer is a shear layer formed by the action of shear stresses at a solid boundary. It is a relatively thin layer with a mean velocity profile starting at zero at the solid boundary and increasing to the freestream at the outer edge. The boundary layer is dominated by the effects of viscosity and there are in theory two distinct types of boundary predicted by the Reynolds number as the ratio of inertia to viscous forces (see

Table I). At low Reynolds numbers (below 10^5) the boundary layer is laminar. At higher Reynolds numbers the boundary layer first becomes unstable with bursts of turbulence and a transition occurs towards a turbulent boundary

The variation of \bar{V}_z (mean velocity at height z) can be approximated by 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. The wind shear power law is:

$$\frac{\bar{V}_z}{\bar{V}_{z_G}} = \left(\frac{z}{z_G} \right)^\alpha \quad (\text{eq. 11})$$

with

z_G = function of ground roughness

α = function of ground roughness

The logarithmic law is:

$$\bar{V}_z = \bar{V}_1 \log_e \left(\frac{z}{z_0} \right) / \log_e \left(\frac{z_1}{z_0} \right) \quad (\text{eq. 12})$$

with

\bar{V}_1 = mean velocity at some reference height z_1

z_0 = roughness length (value equal to about 5-10% of the average height of the terrain roughness elements (e.g. houses, trees, etc.)

An improved form of these laws can be obtained by introducing a "false" ground which varies with the height of the roughness elements of the terrain. This correlation can be significant in densely populated areas where the effective ground plane tends to be nearer the average roof height rather than the true ground level (Aynsley et al., 1977, p.90).

The roughness length z_0 is thereby a parameter introduced to model the horizontal mean wind speed near the ground; in the log wind profile models. It is equivalent to the height at which the wind speed theoretically becomes zero. In reality the wind at this height no longer follows a mathematical logarithm. It is typically related to the height of terrain roughness elements. Whilst it is not a physical length, it can be considered as a length-scale a representation of the roughness of the surface. As an approximation, the roughness length is approximately one-tenth of the height of the surface roughness elements. For example, short grass of height 0.01m has a roughness length of approximately 0.001m.

Roughness length is an important concept in urban meteorology as the building of tall structures, such as skyscrapers, has an effect on roughness length and wind patterns (see also Plan area density in chapter 2.3.2).

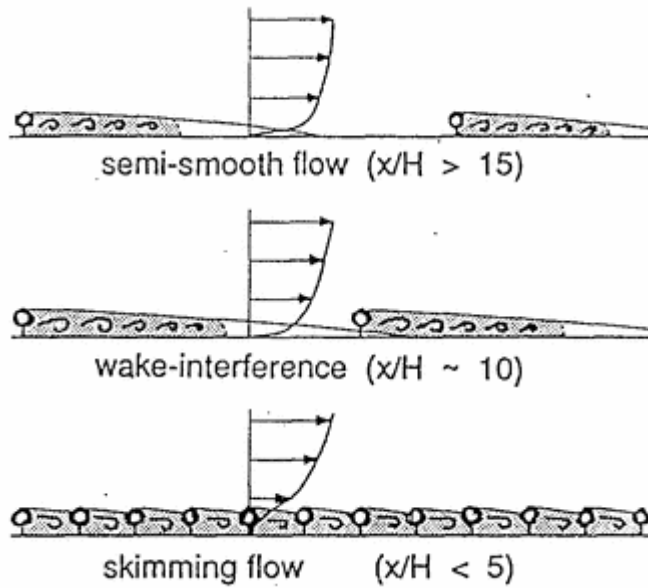


Figure 11 – Flow categories with typical density of terrain obstacles and indication of appropriate wind profile shapes (Wieringa, 1981), where H is obstacle height and x is object height

It is interesting to subdivide the surface aspect of natural terrain according to physical flow behavior (Figure 11). The following four categories are widely used in surface flow investigations (Wieringa, 1981).

- (A) *Smooth turbulent* flow occurs over flat surfaces without any obstacles which are prominent enough to produce noticeable wakes
- (B) *Semi-smooth turbulent* flow occurs over surfaces with isolated obstacles which are sufficiently far apart, that their individual wakes are almost dissipated in the interspaces between the obstacles. In this situation the obstacles form drag and the surface friction drag of the large interspaces are approximately additive (Marshall, 1971)
- (C) *Wake-interference* flow occurs when obstacle interspaces are equal to or slightly less than typical wake lengths – of the magnitude of 5 to 15 obstacle heights H , depending on shape, porosity and distribution of the obstacles. Then the various types of drag are not simply additive, and the flow will nowhere be in equilibrium at levels $z < H$.
- (D) *Skimming flow* occurs when the surface is so closely covered with high obstacles (at relative distance $D \leq 3 H$) that flow in the interspaces between obstacles has a regime quite separate from the bulk flow above (Wieringa, 1993)

Table 2: Roughness length of homogeneous surface types (Wieringa, 1993)

Surface type	Roughness length (m)	Number of references
Sea, loose sand and snow	≈ 0.0002 (U-dependent)	17
Concrete, flat desert, tidal flat	0.0002–0.0005	5
Flat snow field	0.0001–0.0007	4
Rough ice field	0.001–0.012	4
Fallow ground	0.001–0.004	2
Short grass and moss	0.008–0.03	4
Long grass and heather	0.02–0.06	5
Low mature agricultural crops	0.04–0.09	4
High mature crops (“grain”)	0.12–0.18	4
Continuous bushland	0.35–0.45	2
Mature pine forest	0.8–1.6	5
Tropical forest	1.7–2.3	2
Dense low buildings (“suburb”)	0.4–0.7	3
Regularly-built large town	0.7–1.5	4

This means that wind velocities are reduced due to friction (roughness of the surface of the surrounds). The wind shear factor describes the wind distribution over the height of the wind field.

Table 3 shows the correlation between the terrain factor and the wind shear factor for different surrounding settings.

Table 3: Terrain and wind shear factors (Saelens 2003)

Terrain roughness / wind shear factor	z	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

2.4 The role of building design

2.4.1 Overview

In this section the role of building design in terms of geometry (height, width, length), siting (location height, surrounding building height, plan area density) is discussed. Special focus is put on those factors that would increase wind velocities and electricity output. The following topics are discussed:

1. Increasing wind velocities
 - Channeling
2. Urban planning
 - wind shear effects
 - terrain roughness
3. turbulence and wind gusts

2.4.2 Increasing wind velocities

Flow and channeling

The building or group of buildings are three dimensional, permitting flow around a free end, and the incident freestream flow is a turbulent boundary layer with mean velocity increasing with height and turbulence intensity decreasing with height. There are two separate pressure fields which will cause high induced wind velocities.

Flow due to pressure fields

The first type of flow is caused by the pressure distribution on the windward face of a building which is related to the local wind dynamic pressure which increases with height. The resulting pressure gradient, decreasing with height, induces flow vertically down the face below the stagnation point. This flow rolls up into a standing vortex system at the base of the building, causing high wind velocities in this region (Aynsley et al., 1977, p.151). Buildings of near circular platform which promote lateral flow do not produce strong vertical flows. Conversely, rectangular and concave buildings do produce strong vertical flows with consequent high wind conditions in the standard vortex system.

The configuration of upstream buildings can be critical for this flow because under certain conditions the vortex flow behind a lower upstream building can augment the vortex in the front of the larger building, further increasing the high wind velocities at the base (Aynsley et al., 1977, p.151).

The second type of flow is caused by pressure difference between the low pressure wake regions (leeward and side faces) and the relatively high pressure regions at the base of the windward face. Flow directly between these two regions through arcades or around corners can cause very high local wind velocities. The low wake pressure is dependent on the velocity along the top free boundary, that is, the freestream velocity at the top of the building. Hence the taller the building the lower the wake pressure and the higher the velocities which are induced through arcades and around corners for a given aspect ratio. In general this problem is much harder to control because the wake pressure cannot easily be modified.

Channeling

The building form can be augmented to channel prevailing winds. If the freestream flow area is reduced this will lead to an increase in wind velocity (often coined Bernoulli-effect). This principle has been used in the Tobacco tower in Guangzhou, China (SOM) and the World Trade center in Bahrain (see examples figure 5).

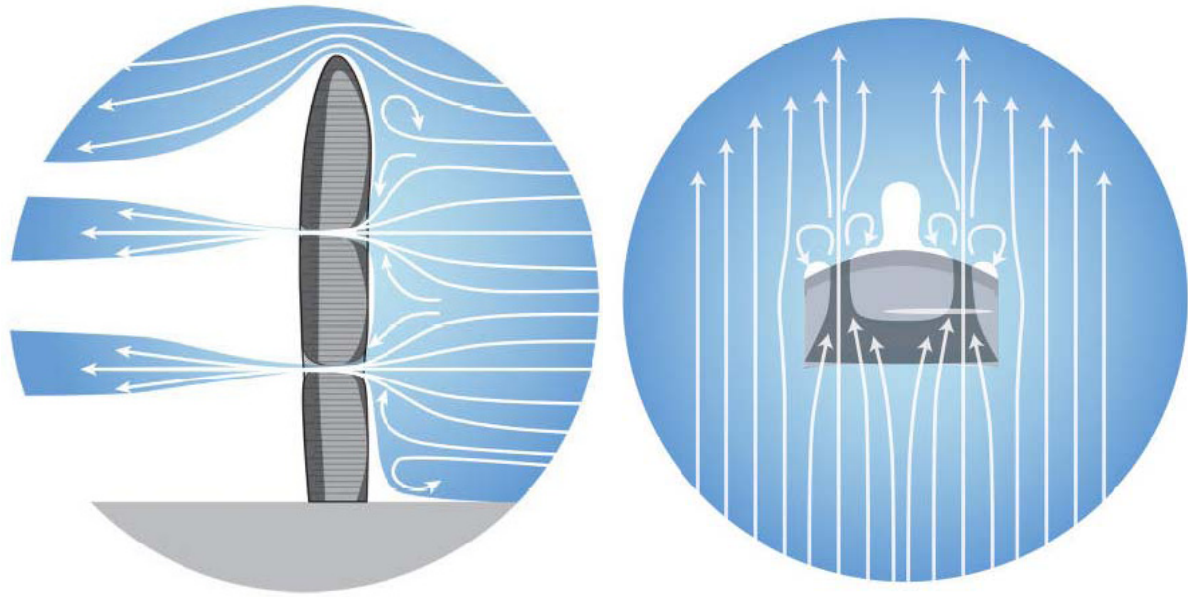


Figure 12 – Channeling effect of the Tobacco tower in Guangzhou (<https://thewaywelive.wordpress.com/2007/03/26/building-integrated-wind-turbines/>) Prevailing winds are channeled through openings in the building where two wind turbines are located (see also Figure 9).

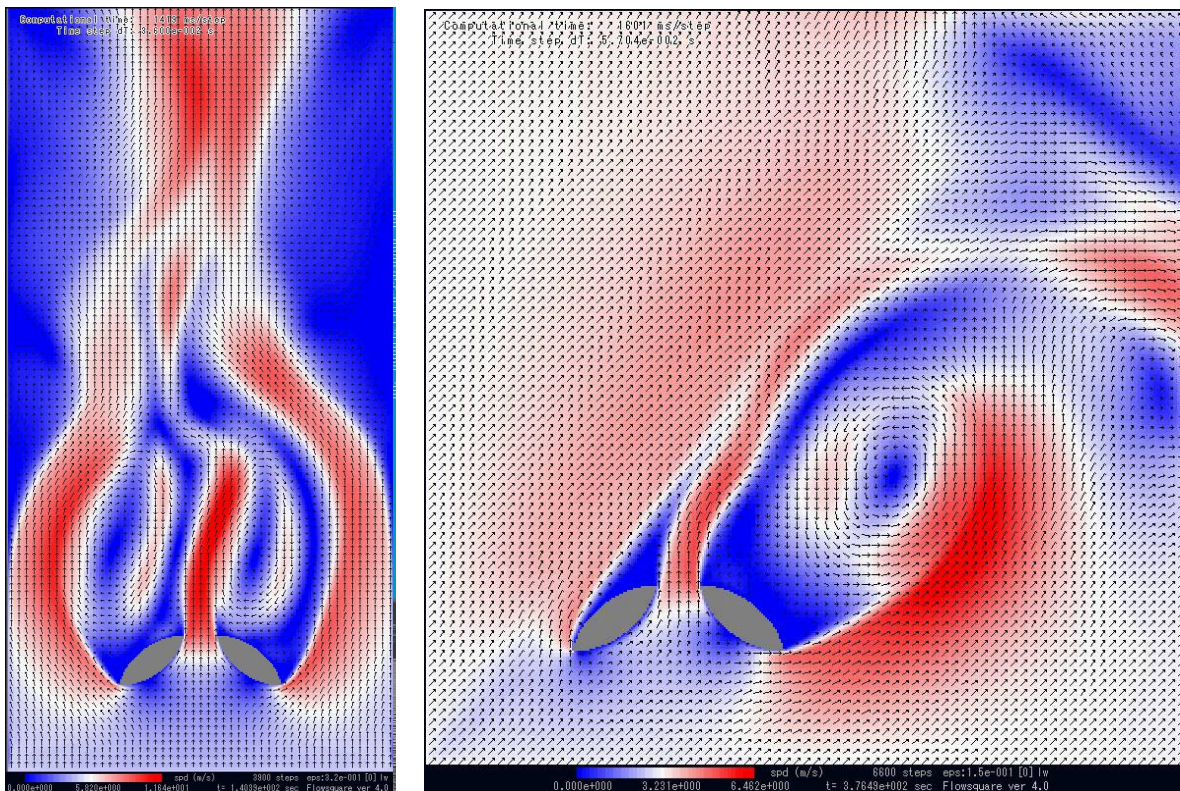


Figure 13 – Channelling effect of the World Trade Center in Bahrain (under two different wind directions). The colour code illustrates wind velocities (blue = low; red = high). The building design channels prevailing winds through the building where wind turbines are located (see also Figure 6)

2.4.3 Urban planning for terrain roughness

Topography and wind

In Norway NS-EN 1991-1-4:2005+NA:2009 include Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions. In chapter 3 of this standard wind velocity and pressures are described which building constructions have to withstand. Wind load depends on the terrain roughness, varies with the height above ground and consists of positive and negative pressure distribution normal to the surface (normally walls and roof structures). Topography and irregular shapes in wind direction can cause large local variations in wind speed. NS-EN 1991-1-4 contains calculation rules for changes in wind velocity due to local topography. It also operates with roughness factors that will influence wind velocity in different heights (see Appendix E for roughness factors). For locations near the top of a hill or slope will wind velocity increase. Wind velocity may also be increased for sites on the leeward side of a steep hill (defined by a slope or rock face has a slope of at least 30 ° and that the horizontal distance to such a slope is less than 15 times the height of the mountain). On the leeward side of a hill with moderate inclination can lead to decrease of wind velocities.

NS-EN 1991-1-4 provides Topography Factors taking into account the change in wind speed because of hills and slopes near the site.

Basic wind speed, v_b , is defined as the mean wind speed over 10 minutes, 10 m above the flat landscape for terrain roughness category II (see NS-EN 1991-1-4) and with a specified return period or annual probability of exceedance. Basic wind speed is defined as:

$$V_b = C_{RET} \cdot C_{ARS} \cdot C_{HOH} \cdot C_{SAN} \cdot V_{REF} \quad (\text{eq. 13})$$

with

C_{RET} = area factor, can be set equal to 1.0.

C_{ARS} = seasonal factor, 0.8 for May to August, or 1.0

C_{HOH} = level factor (altitude)

C_{SAN} = statistical factor, equals 1.0

V_{REF} = reference wind velocity (m / s)

A calculation algorithm has been developed within the frame of the European Research Programme PASCOOL (Passive Cooling of Buildings) of the Commission of the European Communities, Directorate General for Energy in order to able to estimate pressure distribution around buildings (Grosso, 1993). In 1992, the algorithm started to be developed at the Lawrence Berkeley National Laboratory within the COMIS workshop on infiltration and ventilation, and being upgraded within the IEA-ANNEX 23 on multizone airflow modeling (Feustel, et al., 1990; Grosso, 1993; IEA-Annex23). The primary focus was to fulfill the requirements of multizone airflow models, which need a detailed evaluation of the wind pressure distribution around buildings. Scientists and professionals using this program, and who do not have the possibility to test a scale model of their building in a wind tunnel, do not need to extrapolate C_P data from tables usually yielding wall-averaged C_P values (Liddament, 1986).

In order to change wind pressure coefficients on the envelope of a block-shaped building with flat roof the following input variables are important:

- β wind incidence angle (°),
- v : wind velocity (Counihan, 1975)
- sbh : surrounding building height (m),
- pad : plan area density (%),
- building height (m),
- wall azimuth (m)
- the coordinates x and y of the middle of the wind turbine location related to the origin of the building (m) and the frontal and side aspect ratios of the building (m).

Based on these input data, it is possible to calculate the pressure coefficient value at any point on a building surface. *Figure 14 and Figure 15* show how the PAD influences the surface roughness length (R) that has been derived from wind tunnel tests (Grosso, 1993).

From the urban planning point of view the surface roughness of the city or parts of the city can be influenced by the way how urban grids are build and how possible open space is transformed.

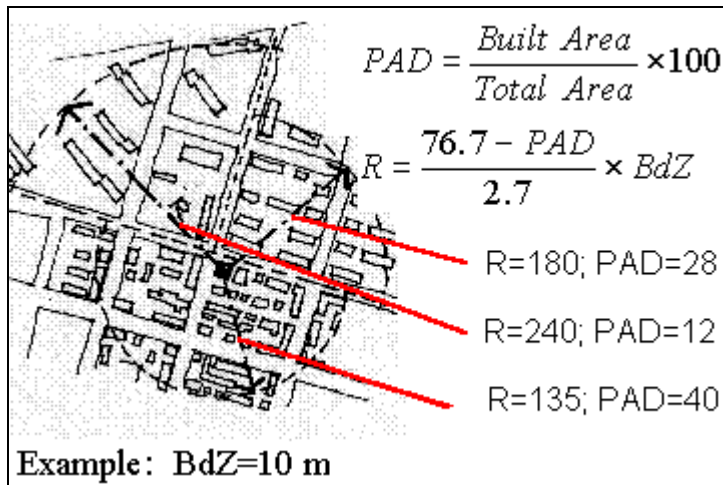


Figure 14 – Plan Area Density (roughness R in meters) (CPCALC, Grosso, 1992)

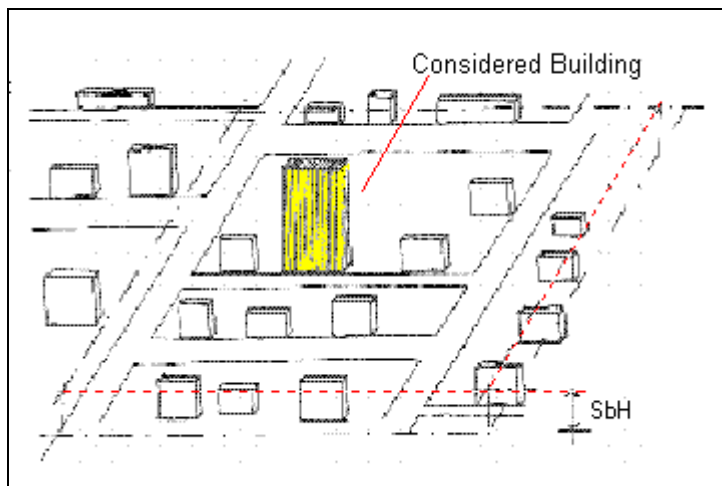


Figure 15 – Surrounding building height SbH (Grosso, 1992)

Possible effects

Table 4 explains the effect of different heights and different terrain factors based on a measurement campaign (see section 2.5) and two different weather stations (both at a height of 10 m). First, measurements of wind velocity were collected (v_{mea}) from a high-rise building in the center of Oslo. Weather stations Blindern and Alna were used and wind velocities at the roof of the building were calculated (v_{calc1}) with a terrain factor of 0.35. The same data from the two weather stations was used with a terrain factor of 0.21 (v_{calc3} , v_{calc4}).

Table 4: Detailed description of wind velocity calculations

	Location of wind measurements	Terrain factor	Height of measurements
v_{mea}	High-rise building near Oslo S	0.35	Measured at roof, 89 m height
v_{calc1}	from weather station Alna	0.35	10 m height
v_{calc2}	from weather station Blindern	0.35	28 m height
v_{calc3}	from weather station Alna	0.21	10 m height
v_{calc4}	from weather station Blindern	0.21	28 m height

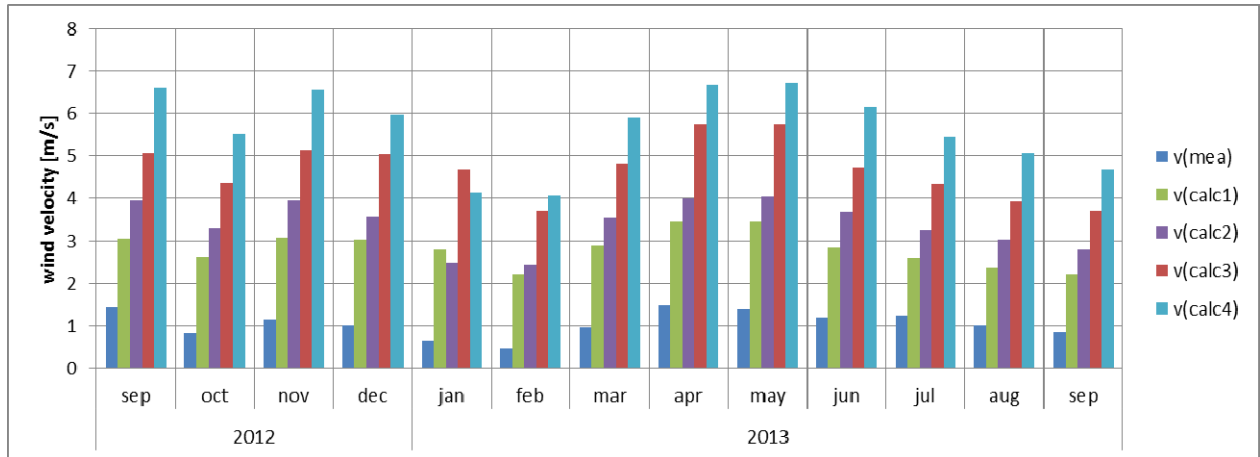


Figure 16 – Monthly wind velocities measured (v_{mea}) and adjusted for height and terrain ($v_{calc, 1}$, $v_{calc, 2}$, $v_{calc, 3}$, $v_{calc, 4}$)

Figure 16 show the results for wind velocities adjusted for height and terrain factor. It can be seen that even with height corrections, measured wind velocities are much lower than expected in the theoretical calculations.

Wind shear effects

Wind shear effects from buildings can be influenced by transformation of existing buildings on district level. Placing a tall building in a low rise neighbourhood will put wind shear effects in action. Local wind pattern will be influenced by this. More work is needed to establish recommendations.

2.4.4 Turbulence and wind gusts

For general application, since typical landscapes almost always contain occasional obstructions, it should be attempted to measure roughness length. The recommended method for estimating the effective roughness length is based on single level gustiness measurements \overline{O}_u .

$$\frac{\overline{\sigma}_u}{\overline{u}_z} = \frac{1}{\ln\left(\frac{z}{z_0}\right)} \quad (\text{eq. 14})$$

Wind measurements for use in (eq. 13) should be made between $20 z_0$ and $100 z_0$; to select the appropriate measurement level, an initial estimate of the effective roughness length must first be made based on a visual inspection of the landscape (select roughness classifications provided in Table 6-10). The sampling duration for \overline{O}_u and should be between 3 and 60 minutes. Data collected for use in estimating the effective surface roughness should be stratified by wind speed (only data for wind speeds greater than 5 m/s should be used) and wind direction sector (using a minimum sector arc width of 30 degrees). Median z_0 values should be computed for each sector; results should then be inspected to determine whether the variation between sectors is significant. An average of the median values should be computed for adjacent sectors if the variation is not significant. Estimates of the effective surface roughness using these procedures are accurate to one significant figure. Documentation of the successful application of these procedures should be provided.

2.5 The role of blade design

2.5.1 Typical key performance indicators

The blade design of a wind turbine is of primary importance. In order to select from the numerous possibilities in blade design it is important to understand the physics. Then typical key performance indicators are introduced that can help to select the best blades (and turbines) for the specific site.

2.5.2 Drag and pull effects

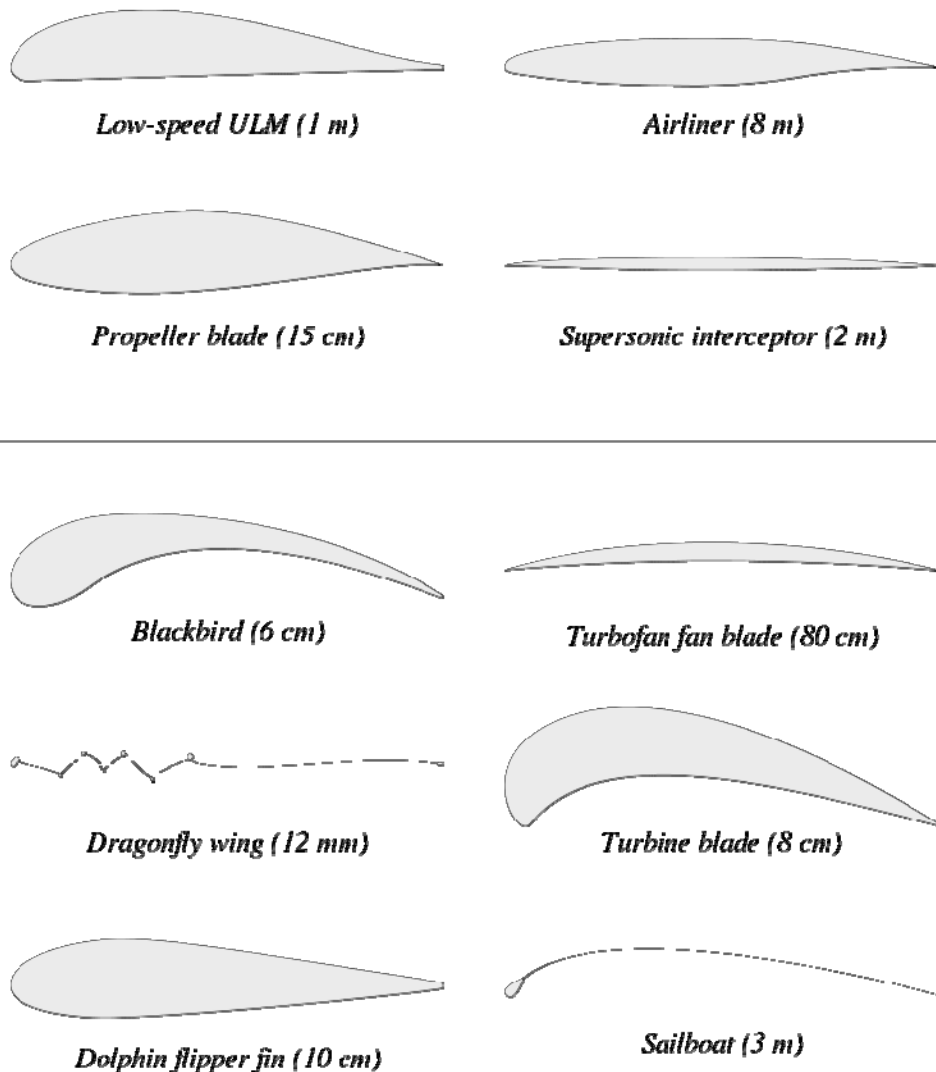


Figure 17 – General blade design (computationalnonlinear.asmedigitalcollection.asme.org)

Blade design details are shown in Appendix C. They have different drag and pull (lift) Rotor blade designers often use classical aircraft wing profiles as cross sections in the outer most part of the blade, but not over the whole length of the blade, which takes a twisted airfoil shape, and makes it more complex to design than airplane wings. The thick airfoil profiles at the innermost part of the blade are designed specifically for wind turbines. The choice of the airfoil profiles for rotor blades involves a number of compromises including reliable lift and stall characteristics, and the profile's ability to perform well even if there is some dirt on the surface.

2.5.3 Tip-speed-ratio

As stated in chapter 2.3.2, 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 .

$$TSR = \frac{\omega \times R}{v} \quad (\text{eq. 15})$$

with

TSR = (symbol) (Hau)

ω = rotor rotational velocity (radians/s)

R = rotor radius (m)

v = wind velocity (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. If the rotor of the wind turbine turns too slowly, most of the wind will pass undisturbed through the gap between the rotor blades. Alternatively if the rotor turns too quickly, the blurring blades will appear like a solid wall to the wind.

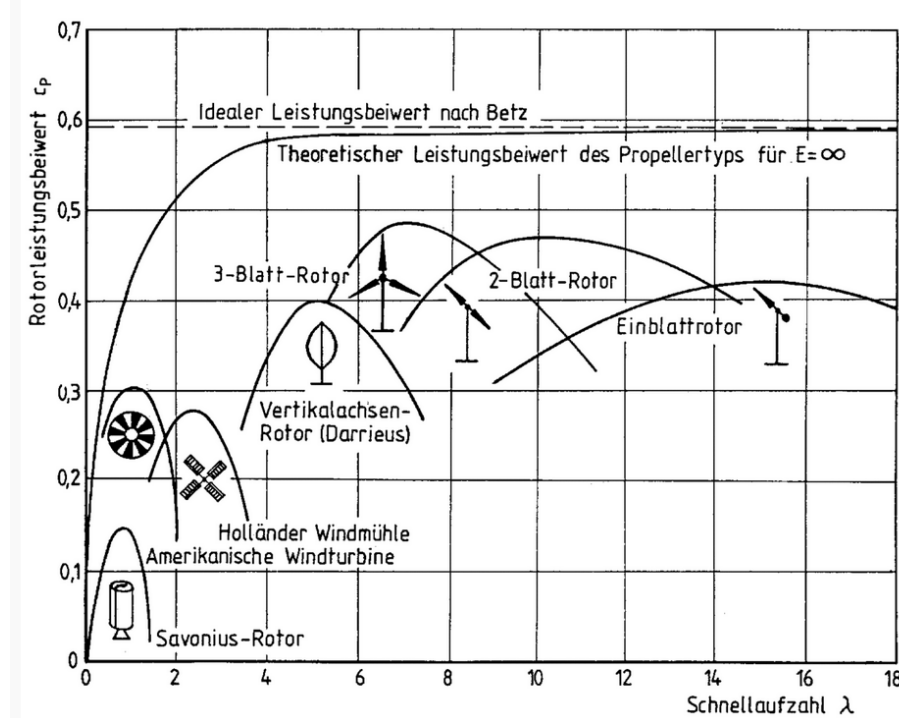


Figure 18 – Power coefficients of different rotor types in relation to TSR (λ) (Hau, 2000)

Therefore, wind turbines are designed with optimal tip speed ratios to extract as much power out of the wind as possible. Figure 18 shows the power coefficients of different rotor types in relation to their TSR. In practice wind turbines with vertical axis that use the drag principle (Savonius-rotor) will have power coefficients between around 0.11–0.14 (Mertens, 2006). Other vertical axis rotors (Darrieus-rotor) provide higher power coefficients up to 0.4.

2.6 Experiences from measurements

This chapter is summarizing results from a study which was done in the period 2012 to 2014. A large property developer asked SINTEF to assist with testing vertical axis wind turbines installed on the

roof of a high-rise building in Oslo. The customer realized that in Norway, the interest in wind generation is extensive, but mostly focused on large scale wind farms. They had difficulties to find guidelines, regulations or specific information about urban wind generation and there seemed to be a lack of knowledge on how to integrate micro wind turbines on buildings. Therefore, they had the intention to test vertical axis wind turbines in the built environment and took the initiative in 2012 to install wind turbines and measurement devices and test the turbines on an actual building under real weather conditions in the center of Oslo.

SINTEF Building and Infrastructure was engaged to make measurements and analyze the results. 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 5* (Haase et al., 2014). More results of the measurement campaign together with more results can be found in Haase et al. (2014).

Table 5 Dimensions of installations (Haase et al., 2014)

	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.)



Figure 19 – Installation of wind turbines and wind measurement devices

The wind turbines in the measurement campaign were vertical axis wind turbines of the type Turbomill™ by Windstream Inc., USA (see *Figure 19*). 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. Haase et al. (2014) gives form and dimensions of one unit with three rotor blades mounted together on a rack. 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 expensive 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 report concluded that 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 and cost reduction. 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 strengths and opportunities in the left column, and weakness and threats in the right column. *Table 6* summarizes the results.

Table 6: SWOT analysis results (Haase et al., 2014)

Strengths: 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	Weaknesses: 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: Emerging technology Increasing environmental awareness increases interest in renewable energy systems	Threats: No standards for electrical connection developed Wind resource in the built environment are poorly understood

3 Evaluation of influencing design parameters

3.1 Parametric analysis

In order to get a better understanding of the parameters that influence the effectiveness of urban wind turbines a parametric analysis was undertaken. The aim was to be able to compare those parameters that will influence wind energy production. The results should not be used for exact energy prediction but rather be understood as estimation that allows wind energy potential comparisons. Based on wind data for three different locations (Oslo, Trondheim and Tromsø; see Appendix F for wind data) a parametric study was conducted that considered the influence of the following parameters:

- wind turbine type
- axis height
- turbine area
- surrounding topography
- wind channeling effect

Three parameters influence the wind velocities while two parameters influence the wind power and electricity production potential. *Table 7* specifies the parameter.

Table 7: Characterization of influencing parameters

Parameter	Influence on wind velocity	Influence on wind power
Wind turbine type		Power coefficient c_p
Axis height	Rotor axis height h_b	
Turbine area		Turbine's active area A
Surrounding topography	Roughness R , α	
Wind channelling effect	Wind velocity factor f_w	
Location	Wind data file	

Wind data is taken from weather data measurements. These are measured for specific locations, often airports, with specific topography. The transformation of measured data to specific sites is not straight forward. In wind projects and relevant literature, often specific data about the surrounding topography of the measurement devices is not available. In addition, PAD and roughness of the surrounding areas of the building where a wind turbine is planned to be installed is not available. For three location, Oslo, Trondheim and Tromsø measured wind data was taken from measurement stations (MET) and transformed using equations (1-12). Hourly data, frequency profiles and duration curves are given in appendix F.

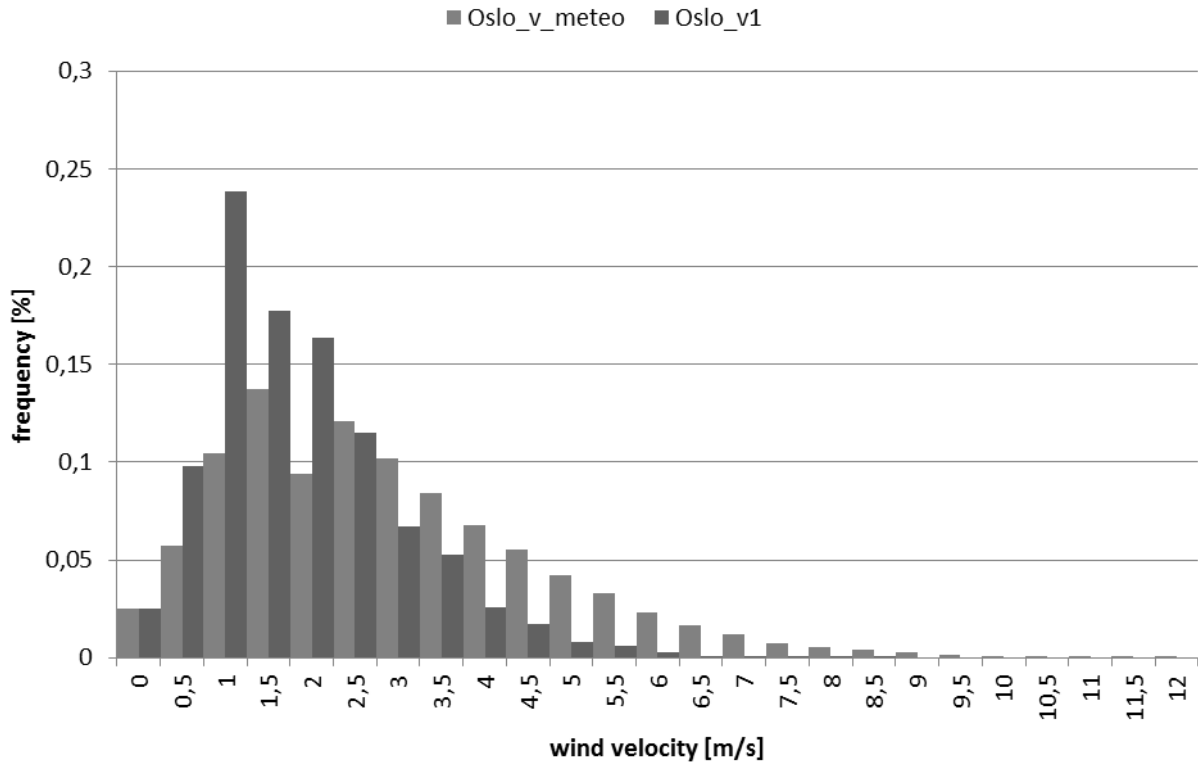


Figure 20 – Effect of topography of measurement station (Oslo)

Figure 20 illustrates velocity profile for Oslo weather file. It shows the frequency of wind velocities (in 0.5 m/s intervals) from the weather file (Oslo_v_meteo) and a transformed profile (Oslo_v1) which takes city topography and a building height of 20m into account. It can be seen that the wind frequency profile is changed showing lower wind velocities with higher frequency.

Velocity profiles can be useful to depict wind availability, distribution and velocity. It can be helpful to put calculation data of wind power and electricity production into the same figure. Figure 21 illustrates the wind power profile of a Savonius type wind turbine. It can be seen that the most frequent wind velocities (between 0.5 and 1 m/s) do not contribute much to wind power and electricity production (below 2kWh). In fact, different turbine types have different specifications with regard to start- and stop- wind velocities. This will reduce the theoretical wind energy production potential. The influence of rotor area and type is discussed in the following sections.

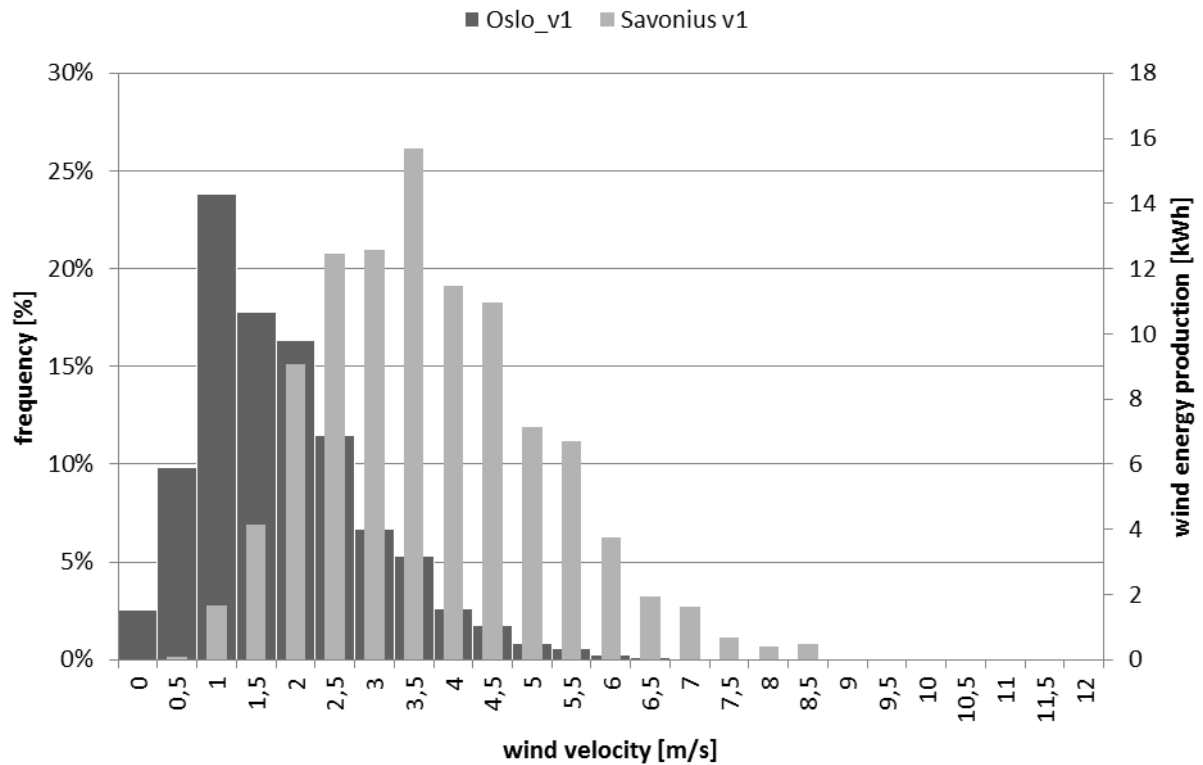


Figure 21 – Velocity and power profile for a Savonius rotor (Oslo)

The influence of rotor axis height and surrounding topography are analyzed further in the following chapters as summarized in Table 8.

Table 8: Further division of parameters in chapters

Chapter	Parameter
3.1	Axis height
3.2	Surrounding topography
3.3	Wind channelling effect
3.4.1	Wind turbine type
3.4.2	Turbine area
3.5	Location

3.2 Axis height

Table 9 defines the different wind profiles for different rotor axis heights.

Figure 22 and Figure 23 show the influence of rotor axis height on wind velocities. Rotor axis height increases wind velocities.

Table 9: Axis height input data used

Axis height	Wind profile	Height (m)
Low	v1	20
Medium	v2	35
High	v3	50

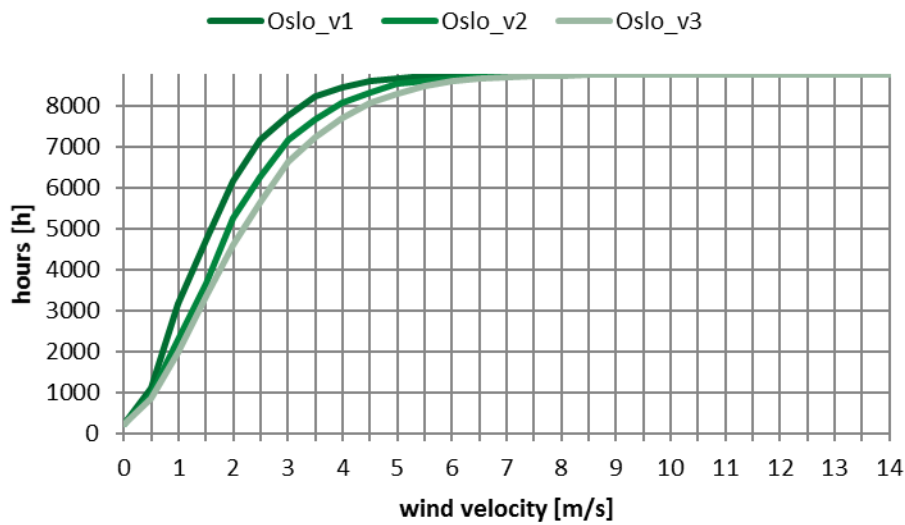


Figure 22 – Effect of axis height on wind velocity duration

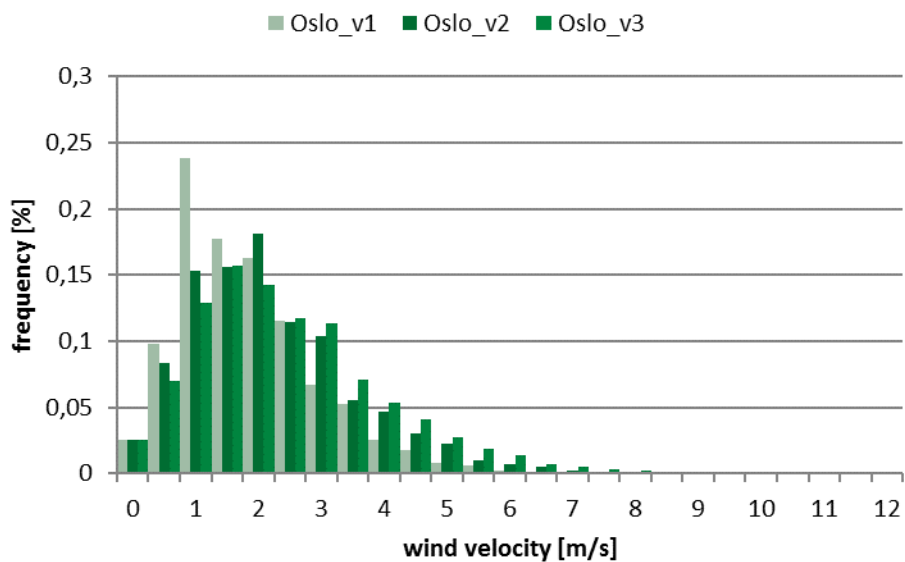


Figure 23 – Effect of axis height on wind velocity profiles (v1, v2, v3)

3.3 Surface roughness

Table 10 shows the details of different topographies (country, urban and city). It can be seen from Figure 24 and Figure 25 that wind velocities are increased for urban topography compared to city topography. The highest wind velocities are resulting for country topography (see also frequency profiles in Figure 25).

Table 10: Surface topography input data used

Surrounding surface class	Wind profile	Roughness R (m)	Profile α
City	v4	0.21	0.33
Urban	v5	0.35	0.25
Country	v6	0.52	0.20

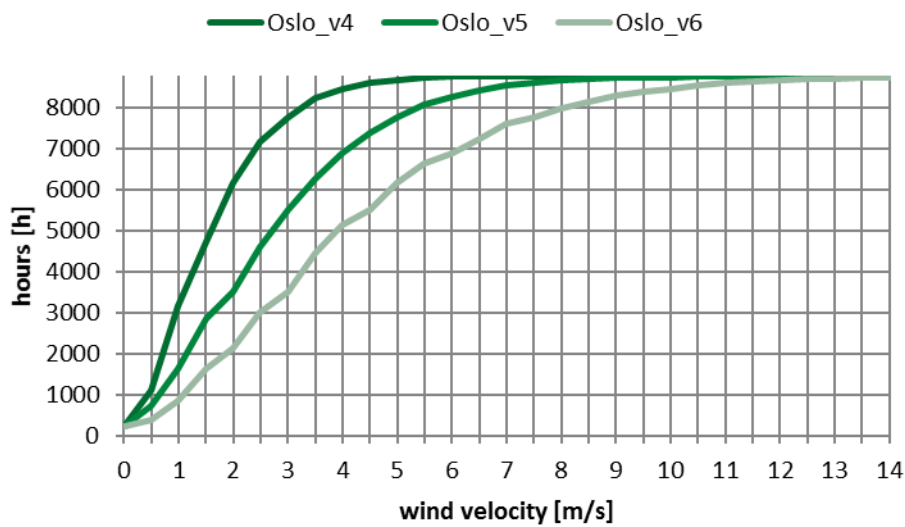


Figure 24 – Effect of surrounding topography on wind velocity duration

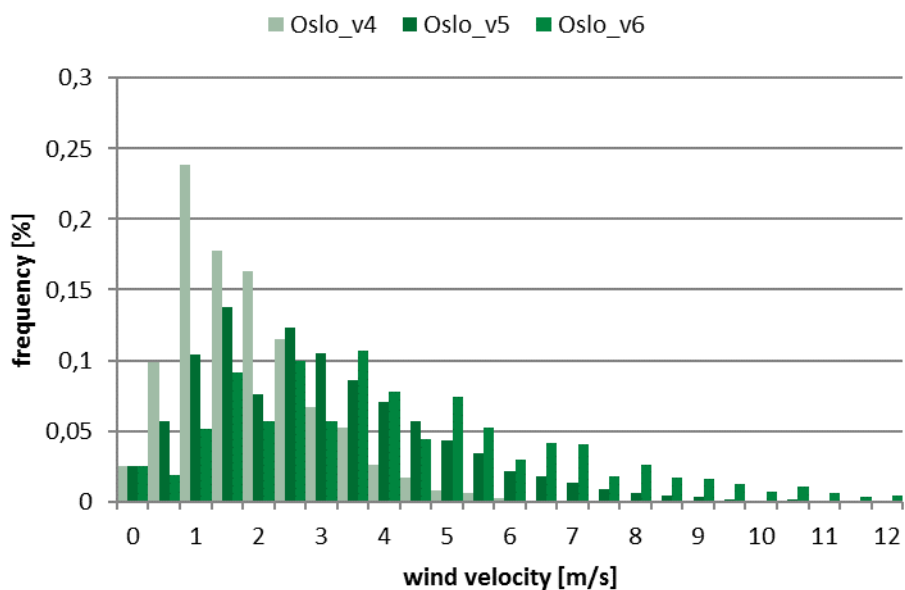


Figure 25 – Effect of surrounding topography on wind velocity profiles (v4, v5, v6)

3.4 Wind channeling effect

Table 11 summarizes the effect of increasing wind velocities by augmented building design. The wind profiles v7, v8 and v9 correspond to wind factors 1, 1.5 and 2 respectively. Here, it was assumed that the building design is augmented so that wind is channeled which will increase velocities with the wind factors. This is a first simplification, since wind velocities normally will only be increased for distinct directions.

The results are illustrated for Oslo weather file in Figure 26 (duration curves) and Figure 27 (frequency profiles). It can be seen that wind velocities are increased for v8 and v9.

Table 11: Wind channelling effect input data used

Building augmentation	Wind profile	Wind factor
Small	v7	1
Medium	v8	1.5
Large	v9	2

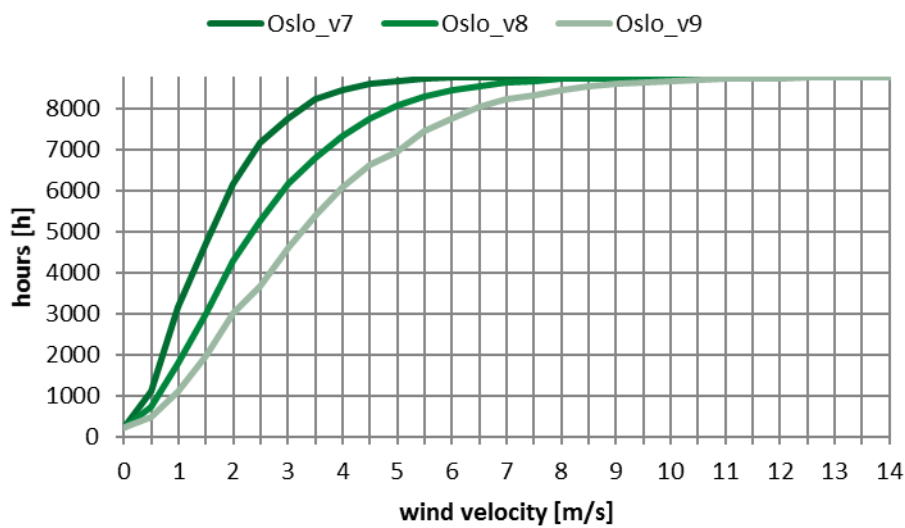


Figure 26 – Effect of wind channeling effect on wind velocity duration

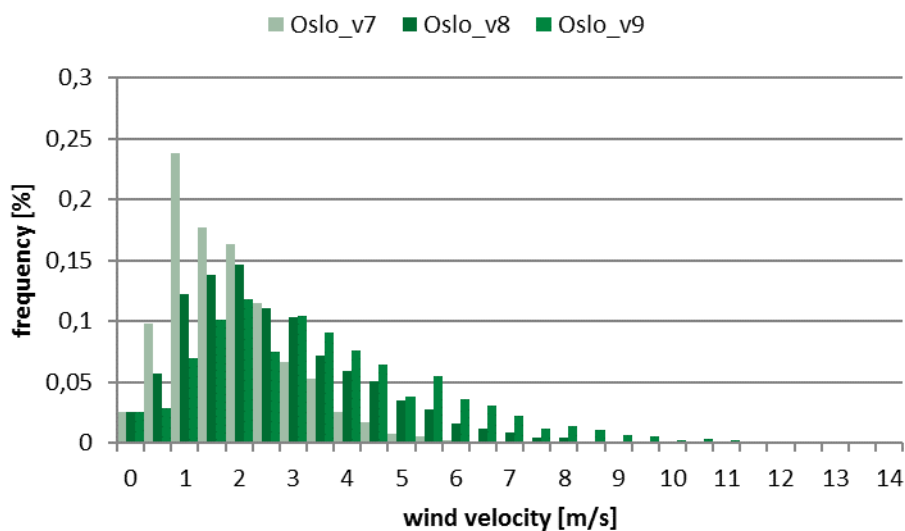
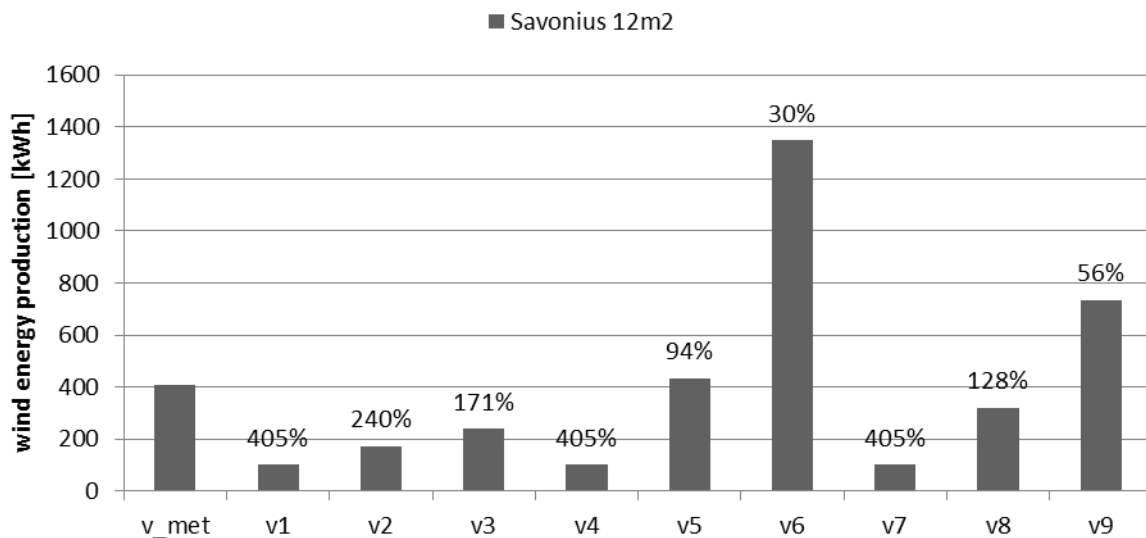


Figure 27 – Effect of wind channeling effect on wind velocity profiles (v7, v8, v9)

3.5 Effect of wind frequency profiles on wind energy production potential

3.5.1 Energy production for the nine wind velocity profiles

In the previous sections nine different wind velocity profiles were developed (v1, v2, v3, v4, v5, v6, v7, v8, v9). These could be used to calculate the wind energy production potential using equations (1-12). *Figure 28* illustrates the wind energy production for the nine wind velocity profiles (for a Savonius rotor type with 12m² effective area). The results depend on those parameters that were identified as influencing wind power and electricity production potential. The wind velocities of the weather file are included in the figures to illustrate how wrong wind electricity production predictions would be compared to the design parameters (in percentage above the columns).



*Figure 28 – Effect of **wind velocity** on wind energy potential*

3.5.2 Wind turbine type

Table 12 shows the different wind power coefficients of different wind turbine types. Different products will have different power coefficients (cp) and these figures are rough assumptions based on (Hau, 2000). It is further assumed that power coefficients remain constant for each type and will therefore only remain rough estimates.

Figure 29 illustrates the effect of wind turbine type on wind electricity production. Please note that the active areas are kept the same size for each rotor type even if this is strongly dependent on product specifications. It was important to make a comparison possible. The relative results for the other turbine sizes (18m² and 24m²) are similar. But it should be noted that different products will have different properties which require a more detailed analysis before deciding on a specific product. Especially cut-in and cut out wind velocities but also the dynamic power coefficient (cp) profile over TSR varies among the same type of wind turbine.

Table 12: Turbine type input data used (Hau, 2000)

Turbine type	Axis	Cp (-)
Savonius	Vertical	0.11
Darrieus	Vertical	0.4
3-blade rotor type	Horizontal	0.5

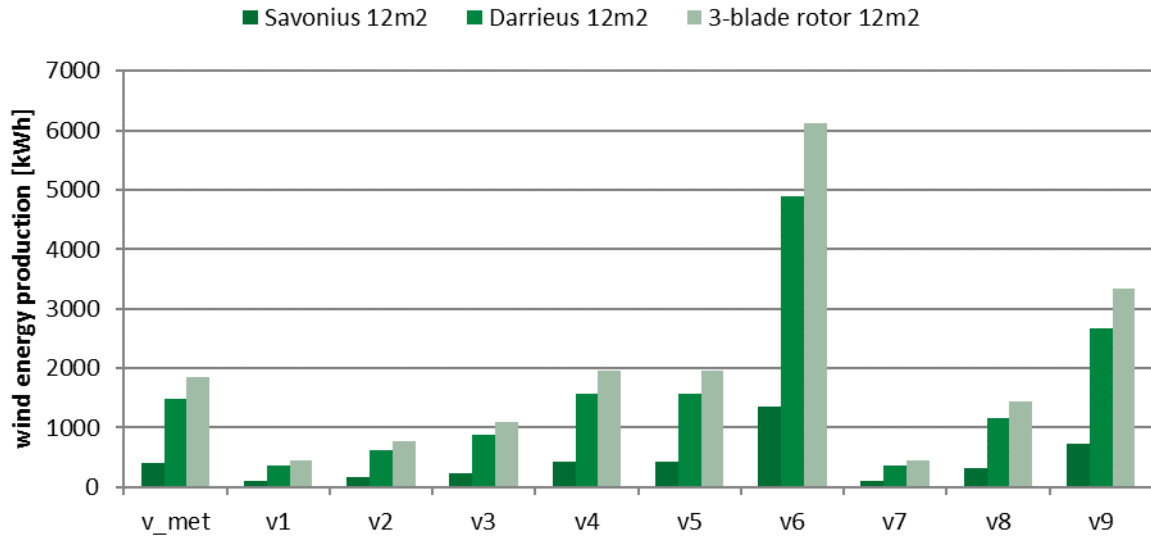


Figure 29 – Effect of **turbine type** on wind energy potential for 12m² turbines

3.5.3 Turbine area

Table 13 shows the active areas for each rotor type. Please note that the active areas are kept the same size for each rotor type even if this is strongly dependent on product specifications. It was here seen as important to be able to make a comparison.

Table 13: Turbine area input data used

Turbine area	Active area (m²)
Small	12
Medium	18
Large	24

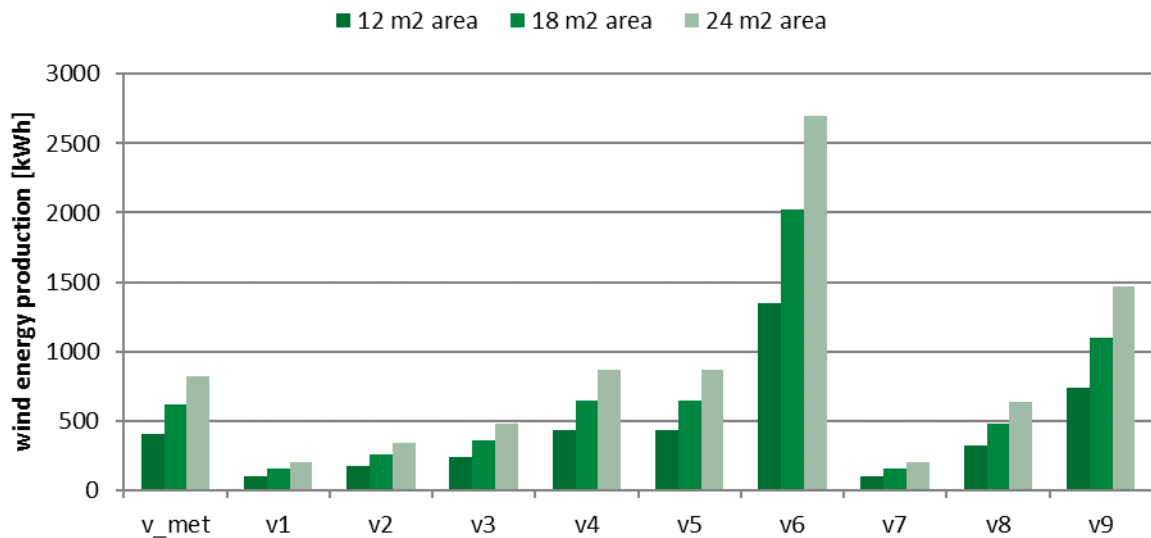


Figure 30 – Effect of **turbine area** on wind energy potential for Savonius rotor type

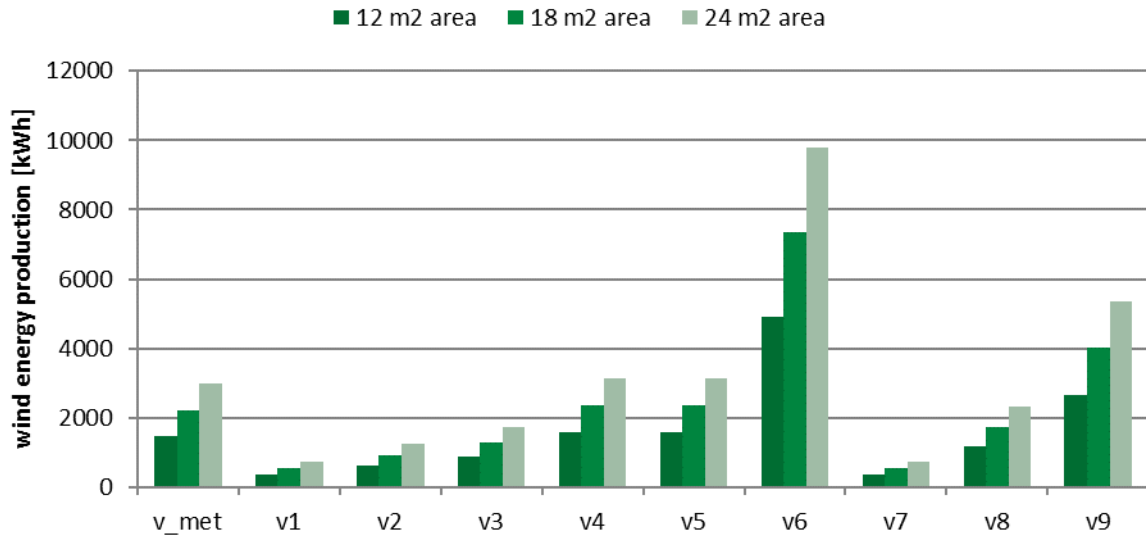


Figure 31 – Effect of **turbine area** on wind energy potential for Darrieus rotor type

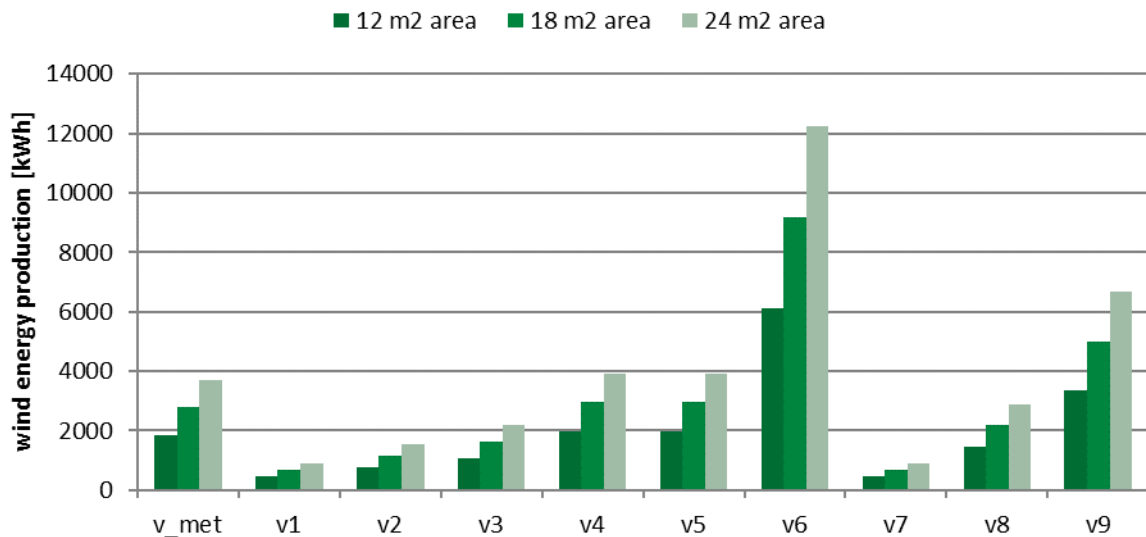


Figure 32 – Effect of turbine area on wind energy potential for 3-blade rotor type

Figure 30 to Figure 32 illustrate the effect of wind turbine area (12m^2 , 18m^2 and 24m^2) on wind electricity production for different turbine types. As expected is the wind energy potential linear to turbine area.

3.6 Location

The location of the wind turbine has an influence on the wind energy production. The results for different turbine types, sizes and locations are shown in Table 14.

It can be seen that wind energy production is highest for Tromsø. This is due to the much higher wind velocities as shown in Appendix E. Compared to Oslo the energy production is 4-5 times higher.

Table 14: Wind energy production potential in kWh per year for different turbine types, sizes and locations

area (m ²)	rotor type	location	v _{met}	v1	v2	v3	v4	v5	v6	v7	v8	v9
12	Savonius	Oslo	409	101	171	239	433	433	1348	101	318	735
		Trondheim	1139	352	597	835	1469	1469	3706	352	1139	2339
		Tromsø	1742	536	913	1280	2275	2275	5515	536	1742	3661
	Darrieus	Oslo	1487	367	621	870	1575	1575	4901	367	1158	2674
		Trondheim	4143	1279	2172	3037	5342	5342	13477	1279	4143	8506
		Tromsø	6335	1949	3319	4654	8275	8275	20053	1949	6335	13312
	3-blade rotor	Oslo	1858	459	776	1088	1968	1968	6126	459	1447	3342
		Trondheim	5178	1599	2714	3797	6677	6677	16846	1599	5178	10633
		Tromsø	7919	2436	4149	5818	10343	10343	25067	2436	7919	16640
	Savonius	Oslo	613	151	256	359	650	650	2022	151	478	1103
		Trondheim	1709	528	896	1253	2204	2204	5559	528	1709	3509
		Tromsø	613	613	151	256	359	650	650	2022	151	478
18	Darrieus	Oslo	2230	550	931	1305	2362	2362	7352	550	1737	4011
		Trondheim	6214	1919	3257	4556	8013	8013	20215	1919	6214	12759
		Tromsø	9503	2923	4979	6981	12412	12412	30080	2923	9503	19968
	3-blade rotor	Oslo	2787	688	1164	1631	2953	2953	9189	688	2171	5013
		Trondheim	7768	2399	4072	5695	10016	10016	25269	2399	7768	15949
		Tromsø	11878	3654	6223	8727	15515	15515	37600	3654	11878	24960
	Savonius	Oslo	818	202	341	479	866	866	2696	202	637	1471
		Trondheim	2278	704	1194	1670	2938	2938	7412	704	2278	4678
		Tromsø	3484	1072	1826	2560	4551	4551	11029	1072	3484	7322
	Darrieus	Oslo	2973	734	1241	1740	3150	3150	9802	734	2316	5348
		Trondheim	8285	2559	4343	6074	10684	10684	26953	2559	8285	17012
		Tromsø	2973	2973	734	1241	1740	3150	3150	9802	734	2316
	3-blade rotor	Oslo	3717	917	1552	2175	3937	3937	12253	917	2895	6684
		Trondheim	10357	3199	5429	7593	13355	13355	33692	3199	10357	21266
		Tromsø	15838	4872	8298	11636	20686	20686	50134	4872	15838	33280

3.7 Summary and conclusion

From *Table 14* can be seen the influence of all the analyzed parameter on the wind energy production potential in kWh per year for different turbine types, sizes, locations and different wind profiles (v1 – v9).

It can be seen that wind energy production varies between 100kWh and 1348kWh for different wind profiles as illustrated in *Figure 28* for Oslo. In order to be able to evaluate the influence of each parameter on wind energy production it was divided by the wind energy production of the weather file for each location. *Figure 33* shows the influence of parameters axis height, surface roughness and wind factor for Oslo, Trondheim and Tromsø. It can be seen that axis height varies between 25% and 59% (compared with energy production from the reference weather data file (v_meteo)). Surrounding surface roughness has a much higher influence with values between 25% and 330%. Here, country roughness is much more favorable than urban and city roughness. For wind factor the values vary between 25% and 210%. This illustrates the need to have local wind velocity profiles to be able to make more accurate predictions.

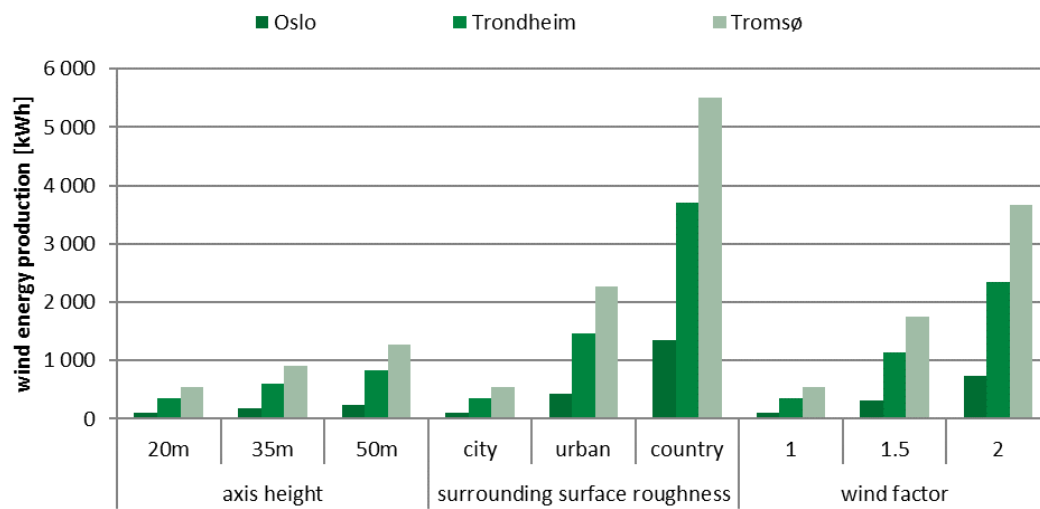


Figure 33 – Effect of influencing parameters axis height, surface roughness and wind factor for Oslo, Trondheim and Tromsø

The other three influencing parameters turbine type, turbine area and location also have a large impact on wind energy potential. *Figure 34* shows that size as well power coefficient c_p of a turbine as has a linear relation with wind energy potential. This is due to the simplifications in the energy calculations that power coefficient is assumed to be constant. Important is also the location. Appendix F shows that wind profiles in Trondheim have higher velocities as Oslo, and Tromsø higher velocities than Trondheim. Wind energy potential is accordingly higher in Trondheim than in Oslo and higher in Tromsø than in Trondheim.

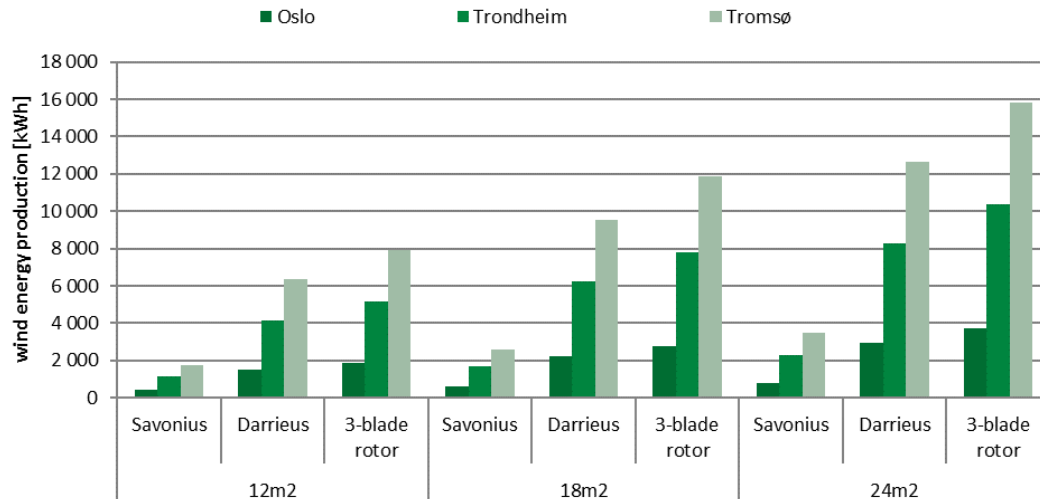


Figure 34 – Effect of influencing parameters turbine type and area for **Oslo, Trondheim and Tromsø**

This could be useful information for designers and planners of small urban wind turbines. The effect of location is very important, together with turbine size type and size. On possibility to present the results is by showing the number of rotors needed to produce 25000kWh. *Table 15* shows results for Oslo. Based on e.g. a 24m² wind turbine with country surface roughness the number of rotors needed for different turbine types (which have different power coefficients) for same wind profiles will be 9, 3 and 2 rotors. Turbine's rotor size is beneficial (18, 12, 2 rotors) but larger rotors become more difficult to integrate into the buildt environment.

Also wind profiles can be influenced by designers and planners by taking building and urban design in to account and specifically focusing on the parameters axis height (between 7 and 11 rotors for 50m axis height), surrounding topography (between 2 and 19 rotors for urban but 27 to 248 for city) and wind channeling effect (between 4 and 34 for wind factor 2). The axis height is strongly linked to the building geometry and especially height as a restricting parameter. The wind channeling effect is most prominent in building augmented projects. But due to the rough assumptions the channeling effect might also be overestimated in these calculations.

Table 15: Results for number of rotors needed to produce same amount electricity as a typical household (25000 kWh) for Oslo

location	area [m²]	rotor type	v_met	axis height			surrounding surface roughness			channeling factor		
				20m	35m	50m	city	urban	country	1	1.5	2
Oslo	12m²	Savonius	61	248	146	104	248	58	19	248	79	34
		Darrieus	17	68	40	29	68	16	5	68	22	9
		3-blade rotor	13	55	32	23	55	13	4	55	17	7
	18m²	Savonius	41	165	98	70	165	38	12	165	52	23
		Darrieus	11	45	27	19	45	11	3	45	14	6
		3-blade rotor	9	36	21	15	36	8	3	36	12	5
	24m²	Savonius	31	124	73	52	124	29	9	124	39	17
		Darrieus	8	34	20	14	34	8	3	34	11	5
		3-blade rotor	7	27	16	11	27	6	2	27	9	4

4 Task 3: User acceptance of augmented wind turbines

4.1 Questionnaire and quantitative study

The background of the project is that new and smaller building augmented wind turbines that could be implemented in the built environment are being developed. This will enable the local production of renewable energy for houses and house owners, either separately or as cooperation with neighbors. This part of the study consists of a questionnaire and a qualitative study. In the qualitative study we have interviewed house owners in order to find out more about not just their willingness to invest in wind power in the urban context as the market looks now. Another aim was to find out what are the issues that would be worth pursuing in relation to the future development and research on small building-augmented wind turbines in particular, but also in relation to local energy production in general.

4.2 Questionnaire

4.2.1 Challenge

A questionnaire is used for quantitative analyzes of peoples' perception of *new and smaller building augmented wind turbines that could be implemented in the built environment*. The challenge is to identify the main barriers in having this new technology introduced as part of the built environment, and, consequently, finding out more about what should be investigated further (research, marketing and development) in order to increase the likeliness of people (house owners) investing in BAWT in the future. The difficulty of asking about a relatively new technology such as this is obvious; people may not have actual experience of the technology in question. Also, the technology available on today's market is not necessarily what will be available in the future. In fact, the study is partly designed to find out more about what issues should be focused on in the future design, construction and marketing of BAWT.

4.2.2 Method

Initially, we have explored the field in order to find out what key factors should be investigated in the study. For this, we have studied the results of other investigations on peoples' opinion in relation to wind power in general, and we have come up with the following factors; economy (investment pay back times), energy efficiency, maintenance costs and efforts, safety issues, aesthetic factors and noise levels. In addition, we want to know more about the different ownership models that might be applicable for the technology. For this, we have used the existing ownership models that are currently being used in relation to wind power in general as a starting point. The impact of these factors are compared both by looking at the respondents' ranking of their perceived importance of the factors and their perception of how well the technology in question does deliver within this factor, i.e. "how important is (energy efficiency)?" and, "How do you value BAWT in relation to energy efficiency?". Both these questions are formulated as close-ended questions, which enables us to compare the factors separately and to rank and analyze these aspects separately.

However, as we are exploring technology that is more or less new and which does not have an established place and function in today's society we are interested in finding out more about the possibilities and thoughts people may have in relation to BAWT, we are also interested in finding answers to open-ended questions, i.e. questions that allow the respondents to provide their own answers. Open-ended questions are more difficult to analyze and for these questions to have any meaning – as it relates to something that is not

clearly defined, BAWT – it is necessary to establish a common ground of understanding. This need was supported by carrying out of a piloting questionnaire that was tested on a limited number of people, which revealed that examples may be necessary for the informant to have any conception of what BAWT might look like. For clarity, we have chosen to do this by providing the informant with informative example pictures that are meant to illustrate the specific technological concepts (such as different types of wind turbines and different means of having them integrated with the building). Naturally, these pictures and illustrations become part of the relevant context of the study itself. Hence, risk is that the examples do limit the understanding of what may be possible within the field, but the risk is minimized by providing information on the nature and context of the study as part of the analysis.

4.2.3 Results

The questionnaire was sent out to a total of about 1000 respondents together with the newsletter sent out by Åfjord utvikling AS. The total number answering the questionnaire was initially only 13, which is why we chose to include a reminder and link to the questionnaire in the same monthly newsletter, that went out to the same respondents. This was more effective and we have received 67 answered questionnaires. As we did have some feedback on the first round of the questionnaire that people did not feel they knew enough about wind power to answer the questionnaire, we included a comment in the second round of sending it out explaining that no knowledge was required for filling out the form.

Number of daily responses

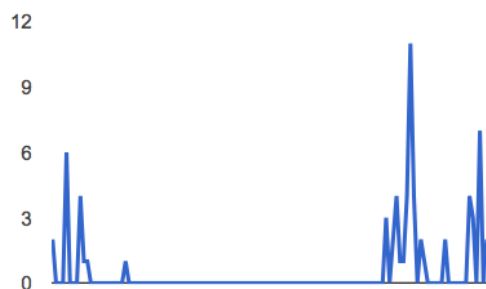


Figure 35 – Number of daily responses as monitored by the system

The questionnaire was answered by a total of 67 informants. Figure 35 illustrates the number of daily responses over the period from June until October 2015. It can be seen that a large number of responses were monitored after reminders were sent out in the end of September 2015.

The results reveal our respondents were in general relatively positive to wind power, with 34,4% of respondents stated they were positive and 35,9 % very positive to it. Only 11% stated they were negative or very negative towards it, and comparably few were negative (15,4%) or very negative (16,9%) toward it being installed in their near vicinity. The question asked was “What is your general impression of Wind turbines? (Here we refer to the traditional type of wind turbine that is present in the landscape today)” and the responses are scaled from “Very positive” (top) to “Very negative” (bottom).

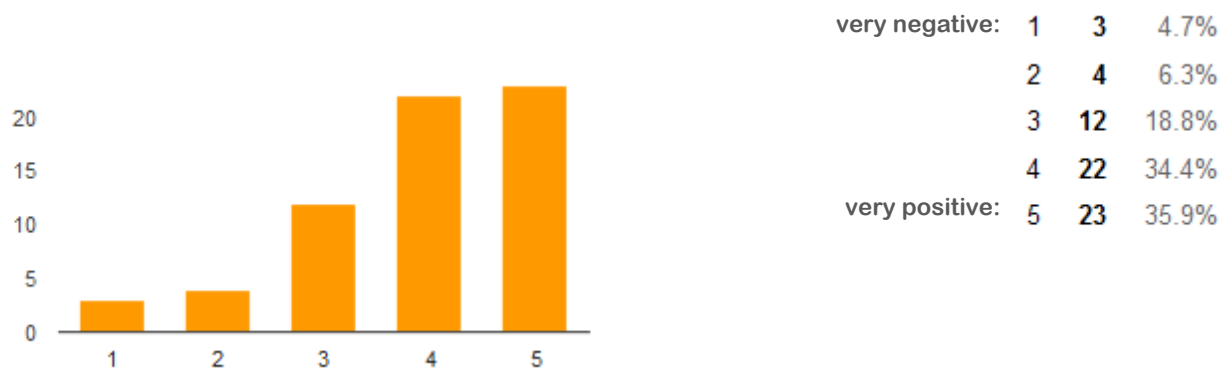


Figure 36 – Question 2: What is your general impression of Wind turbines?

The respondents were also positive towards small scale building augmented wind turbines in general. In addition, less than 15% were negative or very negative towards small scale building augmented wind turbines, and nearly 30% would get actively engaged to promote it being installed in their near vicinity (see *Figure 36* and *Figure 37*).

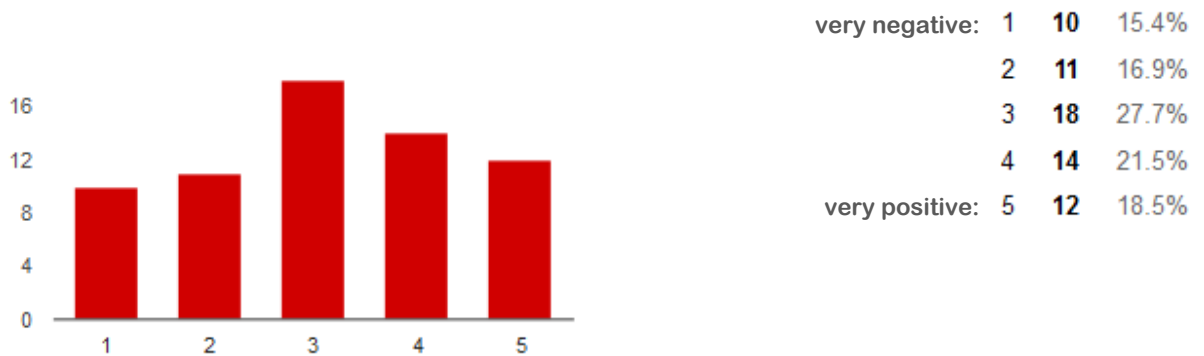


Figure 37 – Question 3: How would you feel about traditional wind turbines being installed in your near vicinity (specify distance)?

Furthermore, the efficiency of small wind turbines was perceived as relatively high (see Question 6 in *Figure 38*), and the efficiency factor was considered an important one (see Question 7 in *Figure 39*), and similar results were found for the factors sustainability (see Questions 10 and 11 in *Figure 42* and *Figure 43* respectively), need for maintenance (see Question and safety (see Question 8 and 9 in *Figure 40* and *Figure 41* respectively). In relation to investment costs, wind power was perceived not as a particularly good investment (economically), but the majority of informants still stated that they would be interested in investing in or installing wind power on their property, indicating that economy is not a major reason for investing in wind power.

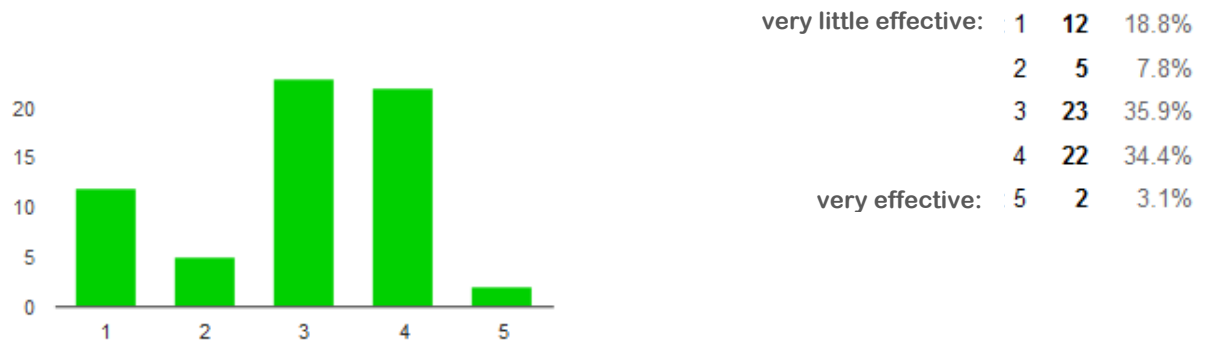


Figure 38 – Question 6: Energy Efficiency: How would you value your impression of smaller building augmented wind turbines in relation to energy efficiency?

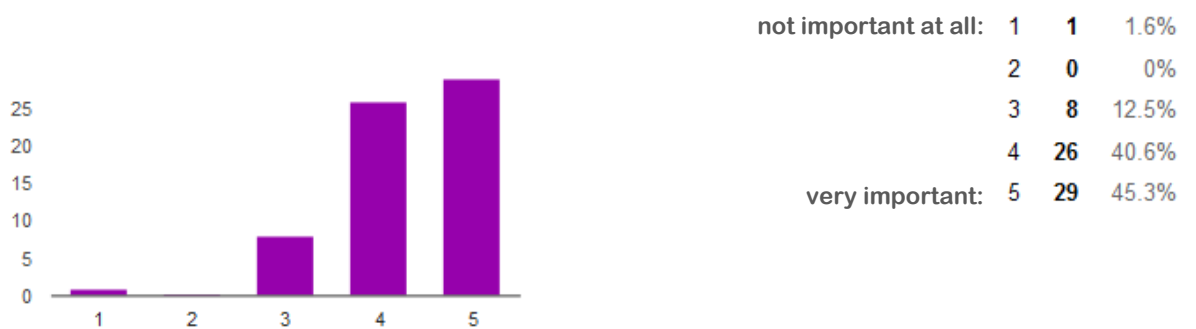


Figure 39 – Question 7: How important is this factor (energy efficiency)?

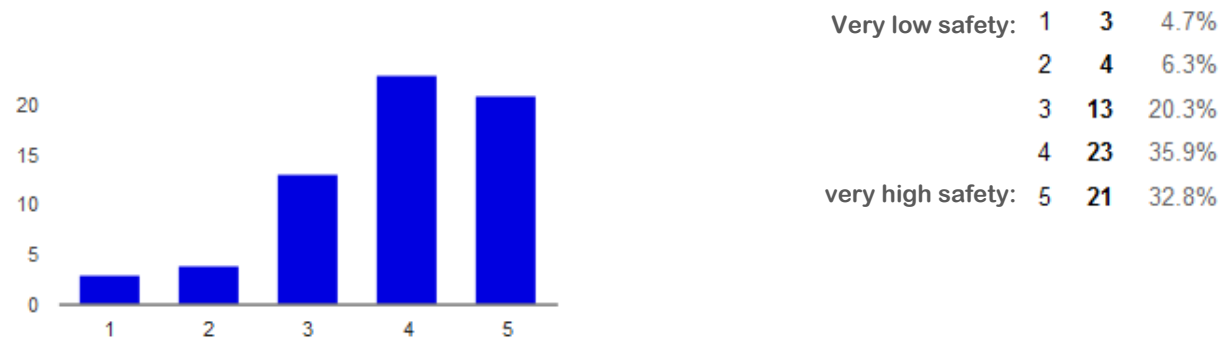


Figure 40 – Question 8: How would you value your impression of smaller building augmented wind turbines in relation to safety?

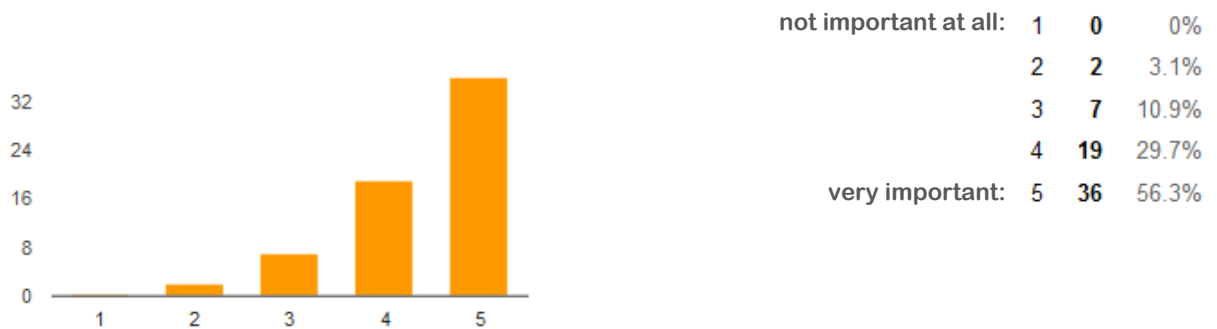


Figure 41 – Question 9: How important is this factor (safety)?

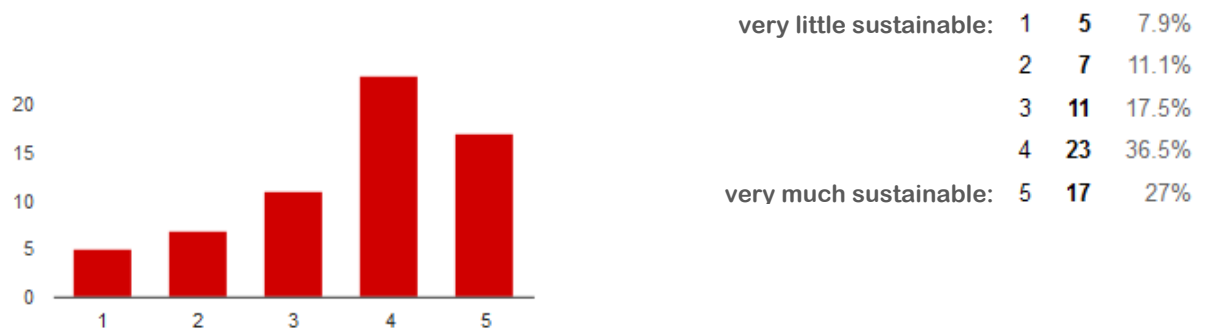


Figure 42 – Question 10: How would you value your impression of smaller building augmented wind turbines in relation to sustainability?

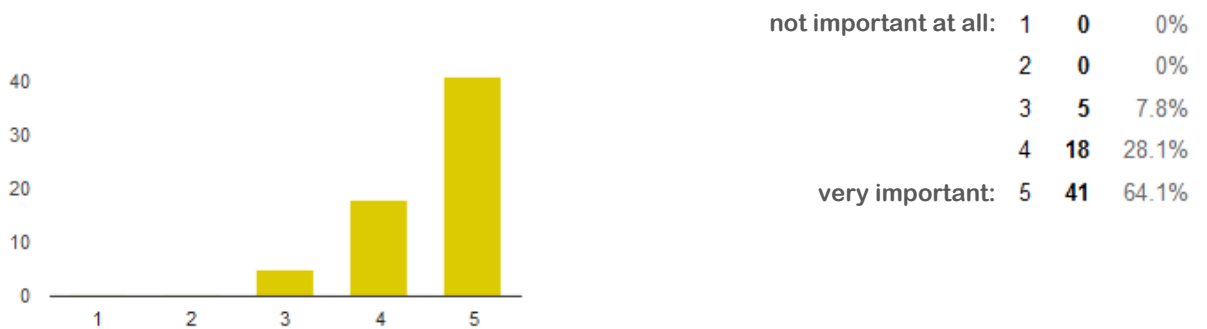


Figure 43 –Question 11: How important is this factor (sustainability)?

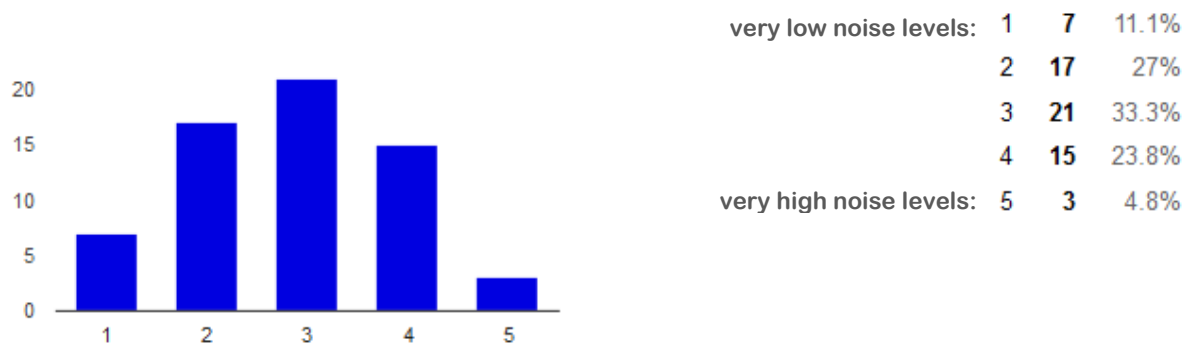


Figure 44 – Question 14: How would you value your impression of smaller building augmented wind turbines in relation to noise levels?

Noise level was considered an important factor, and this seems to be an issue of concern in relation to small wind turbines on buildings (see Question 14 and 15 in Figure 44 and Figure 45 respectively).

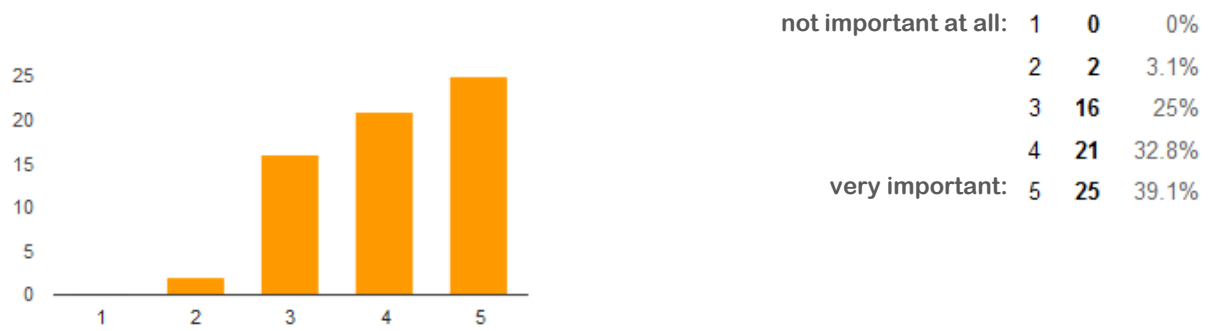


Figure 45 – Question 15: How important is this factor (noise levels)?

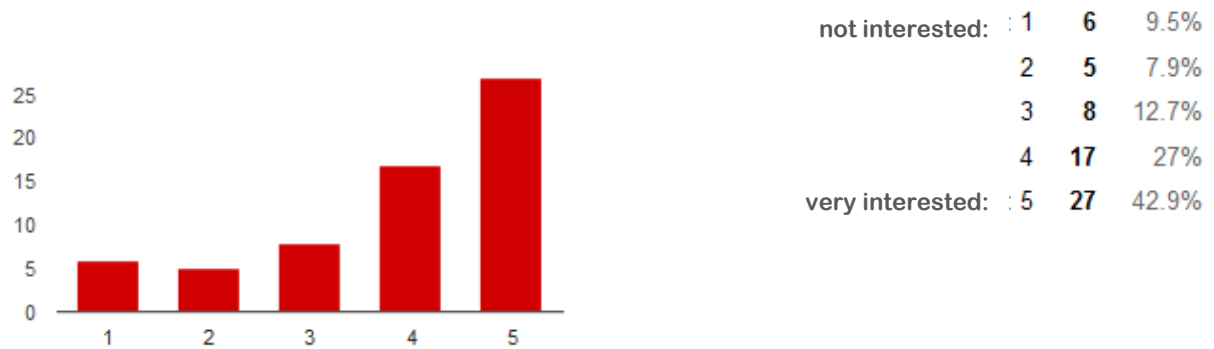


Figure 46 – Question 16: Shared ownership of wind turbines has been a success in for instance Denmark. Would you be interested in co-owning a small-scale wind turbine together with your neighbors?

Using Denmark as an example, we asked whether co-ownership would be interesting as ownership model for wind power, and a majority of respondents stated to be interested in this as shown in *Figure 46*.

4.2.4 Conclusions

The response rate was 6.7% which relatively low for questionnaires. With such a low response rate it is not possible to call the results representative. The low response rate has to be seen in the light of that the content was very technology focused and not everyone has a strong opinion about wind. This might have influenced the results since it might point to the conclusion that only those with a strong opinion about wind did make the effort to answer the questionnaire. Still, there is no argument for that only those with a strong positive or a strong negative opinion did answer the questionnaire.

In general, the results of the quantitative study indicate a general positive attitude towards wind power in general as well as for small scale building augmented wind turbines.

4.3 Qualitative interviews

4.3.1 Background

We have interviewed house owners in order to find out more about not just their willingness to invest in wind power in the urban context as the market looks now, but also to find out what are the issues that would be worth pursuing in relation to the future development and research on small building-augmented wind turbines in particular, but also in relation to local production of energy in general.

In addition to the quantitative data we have collected via the questionnaires, we had added a few qualitative open questions as part of the questionnaire. Many of the informants (approximately 30%) have taken the time to answer these open qualitative questions, which gave us considerable qualitative data based on the questionnaire. The data from these is also reported as part of the Qualitative study.

The results of the qualitative part of the questionnaire reveal some skepticism as to whether small scale wind power in relation to its efficiency. Two of the informants state that wind power is more relevant to invest for their summer house. Wind power is also compared to solar cells and questions are made regarding the combinability of the two. In general, aesthetic aspects seem to be a major issue in relation to wind turbines, and how it is integrated with the built environment seems to be more relevant than whether the wind turbines are placed on the roof or the façade, and whether they are integrated in the building or not (visible or not).

In addition, we have performed 6 semi-structured qualitative in-depth interviews with home owners, providing us with even more extensive qualitative data. The interviews focused on understanding what issues are important for the informants themselves; hence, the interview technique was of a semi-structured form where follow-up questions on themes brought up by the informants themselves were asked.

4.3.2 Method

The qualitative study was carried out in 6 so called semi-structured in depth interviews of 30-50 minutes each. The participants of each interview was the interviewer (r) and the interviewee (i) which represented their household as a whole.

4.3.3 Results

Initially, the interviewee was asked to elaborate on wind power in general, and the standard typical wind turbine that is typically present in the landscape today was used as an example. As it turns out, the interviewees expressed a varying opinion on these. Typically, they all commented on the aesthetic aspects on the wind turbines rather than their performance or risk factors. The impact of wind turbines in the landscapes character was the main issue, and the interviewees were relatively positive to the existence of wind turbines in the landscape, which might indicate a shift in public opinion from the NIMBY (Not In My Back Yard¹) perspective. Two of the informants referred to Denmark and were of the opinion that wind turbines have been a success there, and that this might well be possible also in Norway.

- I actually think that windmills can be quite beautiful. Especially if they are clustered in separate wind-parks that become part of the landscape.

¹ <https://en.wikipedia.org/wiki/NIMBY>

However, all informants are of the opinion that wind turbines should not be placed everywhere and that, if placed in the wrong place, might spoil the landscape and/or the view. In addition to aesthetic factors, safety issues were brought up. The risk for local wildlife (birds) was a concern. However, the interviewees generally would not mind traditional wind turbines being installed in their near vicinity (on their own lawn), providing they did not block the view or otherwise significantly negatively impact their house and lane. If this was the case, however, one informant stressed that she would explore whether she could be compensated (*meaning economic compensation*) for the inconvenience.

- I'd try to get all the advantages I could, of course. (...) But I would not mind really.

Overall, all six informants were relatively positive to traditional wind turbines in general, and their major issues of concern were aesthetic.

In relation to the possibility of having building augmented wind turbines installed as part of the built environment, specifically, this topic turned out to be more or less new to all the informants. Therefore, a number of examples were shown to the interviewees, and the discussions were quite disparate as they all tried to imagine these turbines being installed in their own home surroundings. Again, aesthetic issues were a major concern, and the possibility of having wind turbines becoming a significant part of the buildings was in general a positive idea. However, one concern was that the wind turbines would then have to be an integrated part of the whole architecture of the buildings, which was a positive thing if the building was planned with this from scratch. However, the problem of having these installed and become a part of the already existing buildings was more problematic. However, the traditional small-scale wind turbines that are mounted on the roof seem to be accepted as an additional part of their existing house.

- I wouldn't mind having one of these (meaning traditional ones) on my roof, but for the other ones we would have to rebuild the whole house.

However, in relation to the traditional roof mounted wind turbines, the issue of it being a smart investment was brought up, and four of the six household representatives said they would prefer to share the investment with a neighbor or co-owning it with the whole neighborhood. Maintenance costs were also a concern for three of the interviewees, and the need for professional help in installing and handling the equipment was stressed.

The possibility of having wind turbines as part of the buildings architecture, the interviewees were positive to the examples shown to them (in corner and, in the middle of the façade), but the issue of it seeming like something that may be better suited in the more dense urban environment was raised. However, the overall impression was that they informants would accept the building augmented wind turbines as part of the urban environment, and that they may be willing to invest in such technology if it would be suited for their house of neighborhood. As one of the informants said:

- I actually think it would be quite beautiful if we could have the production of electricity become a natural part of the buildings (...) It would accentuate the consumption on an everyday level. And possibly this may change things...

In addition, three of the informants stressed that if the wind-turbines were to be successfully integrated into the building, this alternative was more appealing than having wind-turbines of traditional or of other types (vertical –axis) mounted on the building separately.

To conclude, the informants were all willing to accept both traditional wind turbines and building-augmented wind turbines, specifically, as part of the built environment. Some issues concerning investment and maintenance costs were raised, especially in relation to

building augmented small scale wind turbines, but these concerns are likely to be overcome. The willingness to invest is considerably larger if the ownership could be shared with others, indicating that co-ownership models for BAWT should be investigated further. Overall, the aesthetic issues were stressed as a major factor. The acceptance of building-augmented wind-turbines as part of the architecture (i.e. integrated in the facade, et cetera) was high, though issues were raised as to whether this could be successfully integrated into existing buildings. However, if the wind-turbines were to be successfully integrated in the building, this alternative was considered more appealing than having wind-turbines of traditional or of other type mounted on the building. Noteworthy was the fact that the risk of noise from wind turbines did not come up as an issue of concern amongst the informants. Also, the risk factor (safety) does not seem to be a factor of major concern in relation to wind turbines.

4.3.4 References

- In depth interviews with six house owners (representing their household), August 2015, Interviewer: Erica Löfström
- Questionnaire on wind power (Please see attachment)

4.4 Conclusions and recommendations based on user acceptance study

The results of the quantitative part of the study indicates that building augmented wind turbines would be well worth pursuing, but that noise levels should be a focus of attention in the further development – and at a later stage in the marketing – of this technology. We found that there is a general willingness to invest in this technology, and that co-ownership with neighbours would be models worth pursuing in this context. Furthermore, the investment costs was not a major driver in relation to the willingness to invest in wind power.

With a low response rate of 6.7% it is difficult to evaluate how representative the results are. However, the participants do not represent a certain group and have not been selected with specific criteria. Therefore will the results represent the larger group that was invited despite the low response rate.

The qualitative study revealed that aesthetic factors are of major influence and wind turbines were even considered aesthetically pleasing. Therefore, aesthetic factors should be specifically targeted in the further development of building augmented wind turbines as should its integration with the built environment. Furthermore, the symbolic values of wind power and its combinability with solar power should be investigated further. Different ownership models and especially co-ownership should be specifically investigated. In addition, the technology might be more relevant in relation to summer houses than for the urban environment. However, this may well change once small scale building augmented wind turbines of different models and placement on the buildings have been developed, especially since aesthetic factors is considered so important in relation to wind power in general.

5 Task 3: Integration issues

5.1 Overview

Wind power as a generation source has specific characteristics, including variability, geographical distribution, favorable economics and, above all, abundance and environmental benefits. Large-scale integration of both onshore and offshore wind raises challenges for the various stakeholders involved, ranging from generation, transmission and distribution, to power trading and consumers. In order to integrate wind power successfully, a number of issues need to be addressed in the following areas:

- **Design and operation of the power system:** reserve capacities and balance management, short-term forecasting of wind power, demand side management and storage and optimization of system flexibility;
- **Market redesign issues:** market aggregation and adapted market rules increasing the market flexibility particularly for cross-border exchange and operating the system closer to the delivery hour; and
- **Grid connection of wind power:** grid codes and power quality and wind power plant capabilities;
- **Grid infrastructure issues:** optimization of present infrastructure, extensions and reinforcements, offshore grids and improved interconnection;
- **Institutional issues:** stakeholder incentives, non-discriminatory third party grid access and socialization of costs

5.2 Norwegian power system

5.2.1 History and status – some numbers

The Norwegian power system and electricity production is based on hydropower. Historically this has made it possible to have low electricity prices and a large energy intensive industry as well as use electricity for heating of buildings. In addition to being rich with hydrological resources, the Norwegian continental shelf is abundant with oil and gas reserves, which have made Norway a large exporter of crude oil and the second largest supplier of natural gas to Europe.

Through negotiations with the EU, Norway has pledged that 67.5% of its energy consumption will come from renewable energy by 2020 (compared to 61% in 2010). Even though Norway is not an EU member state, the country participates in the EU Emission Trading System (OED, 2012). It is believed that Norway may play an important role in reducing emissions abroad by exporting renewable energy (including hydro, onshore and offshore wind, as well as biomass), but also by offering reductions from carbon capture solutions as they mature (SERN, 2013).

The Norwegian net generation was 134.2 TWh in 2013 (124.4 TWh in 2010). In 2013 the share of the hydro plant generation accounted for around 96 % of the total Norwegian net generation. The Norwegian net exchange of power changed from 7.6 TWh net import in 2010 to 4.4 TWh net export in 2013 (SERN, 2013). These numbers illustrate the importance that the weather conditions have on the net generation capacity. A large reservoir capacity provides flexibility, but still it is vulnerable to dry years, which is emphasized in combination with cold weather and the high heating demands of the building stock.

5.2.2 Policies and normative which regulates the renewable energy sector

The overall target of the Norwegian energy and climate policy is to reduce greenhouse gas emissions by 30% (compared with 1990) by 2020 and to be carbon-neutral in 2050, taking into account the country's contribution to emission reductions abroad (Rosenberg, 2013).

Norway has chosen to cooperate on meeting their renewable energy target of 67.5% by 2020 in a common green certificates scheme with Sweden, introducing the certificate scheme in 2012. This mechanism ensures that the renewable energy installations will be deployed where it is most cost efficient to do so (SERN, 2013).

The industrial sector contributed most to Norwegian final energy consumption in 2011, with 29.8%. Household energy use has also been identified as an area for further efficiency gains. The Norwegian government has predominantly been focusing on reducing consumption in the buildings sector as a whole, with the state enterprise for energy efficiency, Enova, instituting a number of appliance and product labelling measures to influence household purchasing decisions. Enova also manages the Energy Fund, which is a government fund established to ensure a long-term, predictable and stable source of finance for energy efficiency and the promotion of renewable energy (SERN, 2013). In 2014 new programs were introduced for commercial building owners/ developers to support investments to realize energy efficiency potential in existing buildings, introduction of innovative building technologies, and restructuring to renewable heating plants (Enova, 2013).

5.2.3 Optimization of present infrastructure

The Norwegian transmission system operator Statnett's investments have increased in recent years to carry out grid developments and improve the transmission grid both domestically and abroad. There are plans to build several new cross-border interconnections in order to strength the integration between the Nordic electricity market and the rest of Europe (by doubling the capacity to Europe within the next decade). This includes possible connections by Statnett to Germany, UK and the Netherlands as well as between its own regions (Statnett, 2013). In relation to this a debated idea has been to offer Norwegian hydropower on a larger scale, as the storage capacity could be used to offset the intermittent nature of renewable energy. This is an argument for the need to increase the electricity production in Norway (Karlstrøm and Ryghaug, 2014). However, it will require tremendous investments in pump-storage power plants and large capacity interconnections (Midttun, 2012).

5.3 Market redesign issues

Figure 47 show that for the past years, monthly electricity end-use in January was more than double of July. The average electricity price is shown to fluctuate accordingly, which make investments in energy efficiency measures aimed at reducing electricity consumption in the cold season particularly viable (NVE, 2011).

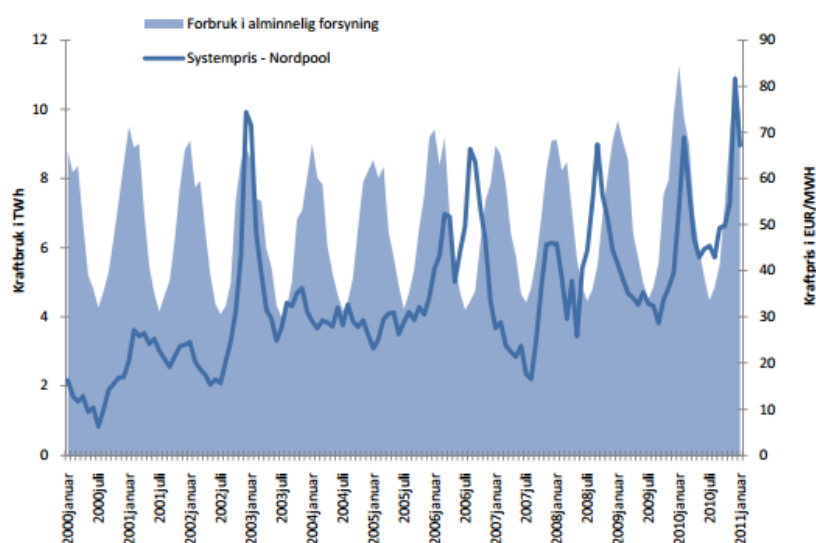


Figure 47 – Monthly end-use electricity consumption and the average system price on the Nordpool market in EUR/MWh (NVE, 2011).

Norway has adopted a strategy for development of offshore wind power and is planning to expand hydropower production by utilizing previously untapped hydropower potentials (smaller unprotected watercourses) and by refurbishing some older installations for increased effect. The total installed generation capacity at the end of 2012 was 32,715 MW. Net increase in hydropower generation capacity during 2013 has been about 379 MW (1.25 TWh), amounting to ca. one-thirds from older installations, new hydro power (<10MWh) and wind power (NVE 2014).

5.4 Grid connection indicators

In the literature *Load matching and grid interaction indicators* (LMGI) have been described by Widén, Wäckelgård and Lund, (2009); Voss and Musall (2011); Kurnitzki et al. (2011); Salom et al. (2014) and Sartori et al. (2012).

IEA Task 40 also focuses in the analysis of load match and grid interaction indicators in net zero energy building. The most relevant indicators of interaction are listed below, which help to evaluate grid interaction and to identify needs to modify interconnections (IEA – task 40).

- **Load Match Index**

It describes the degree of utilization of on-site energy generation related to the local energy demand. It is defined as the average value over the evaluation period of what fraction the energy load is covered by the generation.

It is intended to describe the matching and a high load match means that a great fraction of the load is covered by the on-site generation, while a low value means that the generation covers only a small fraction of the demand. The simplest formula available is the following:

$$f_{load} = \frac{1}{N} \cdot \sum_{year} \min \left[1, \frac{g(t)}{l(t)} \right]$$

with

f_{LOAD} = load match index

N = number of samples (e.g., months, days),

$g(t)$ = energy generation over the period of interest

$l(t)$ = energy load over the period of interest

- **Load Cover Factor and Supply Cover Factor**

The load cover factor (γ_{load}) represents the percentage of the electrical load covered by electrical generation. The complementary index, the supply cover factor (γ_{supply}), represents the fraction of the on-site generation used by the building.

$$\gamma_{load} = \frac{\int_{t_1}^{t_2} \min[g(t) - S(t) - \zeta(t), l(t)] dt}{\int_{t_1}^{t_2} l(t) dt}$$

$$\gamma_{supply} = \frac{\int_{t_1}^{t_2} \min[g(t) - S(t) - \zeta(t), l(t)] dt}{\int_{t_1}^{t_2} g(t) dt}$$

with

$g(t)$ = energy generation over the period of interest

$l(t)$ = energy load over the period of interest

$S(t)$ = storage

$\zeta(t)$ = losses

Both are useful to illustrate both the daily and seasonal effect, the production of pattern of different RES technologies and the applied operation/control strategies including storage.

- **Grid interaction Index**

The Grid Interaction index indicates the variability of the exchanged energy between the building and the grid within a year normalized by the maximum absolute value.

$$f_{grid} = STD \left(\frac{ne(t)}{\max(|ne(t)|)} \right)$$

5.5 Grid codes and power quality

There are several ways to display the load matching and grid interaction. Regarding load matching the following three give a good picture of the correlation between on-site demand and supply of energy:

- Load cover factor – the percentage of the electrical demand covered by on-site electricity generation
- Supply cover factor – percentage of electricity generated on-site that is used by the building
- Load match index

It is possible to illustrate both the daily and seasonal effect, the production pattern of different renewable energy technologies, and applied operation/control strategies. The advantage of factors over energy demand and energy production profiles is the possibility to take into account the influence of different types of storage, e.g. batteries, building thermal mass. Moreover, when computing the load cover factor, we can investigate the influence of different strategies and measures of load modulation, e.g. demand side manager.

The hourly supply cover factor is a good indicator of when and how much of the on-site supply is self-consumed, and thus indicates the periods when building acts as supplier of energy. It should be noted that without knowing the characteristics of the local energy systems, it should not be concluded if high or low cover factors are preferable.

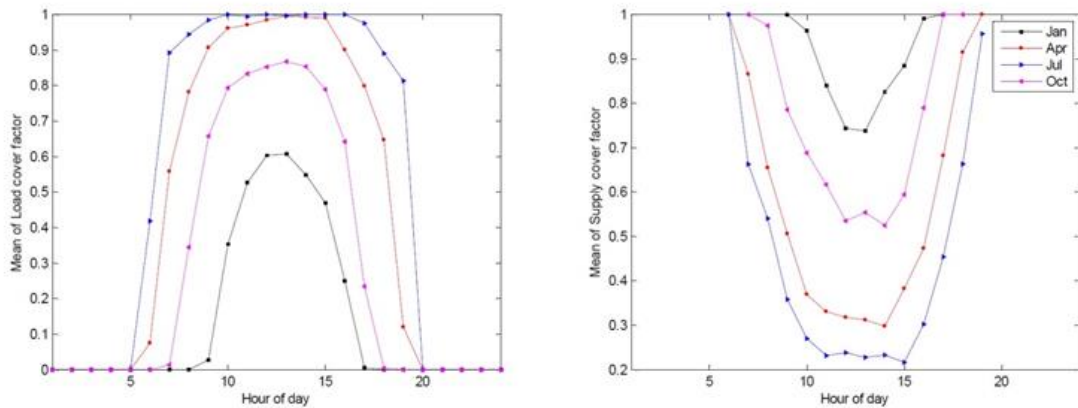


Figure 48: Example of load cover factors (right) and supply cover factors (left) represented as mean values for four months (Salom et al., 2014).

For grid interaction there are two factors considered to be the most indicative:

- Generation multiple – relates the size of the generation system with the design capacity load, expressed as the ratio between generation/load peak powers or exported/delivered peak powers.
- Dimensioning rate – expressed as the ratio between maximum absolute value of the net exported energy divided by designed connection capacity

Grid interaction refers to the energy exchange between the building and the power grid. Graphical representation of net exported energy in load duration curves has been proven to be a useful way to concentrate a lot of information in the same graph: delivered and exported peak values, amount of time when the building is exporting or demanding energy to or from the grid, period when the building is self-sufficient if a storage system is present, etc. Several buildings could be compared if this information is presented in a normalized form related to the connection capacity, together with information on what extent the building is using the grid. Generation Multiple (GM) is an index which relates peak values for exported/delivered energy and also can be used with generation/load values. Dimension Rate (DR) relates the building with the electrical grid although the designed connection capacity of the grid, $\overline{G_{des}}$, needs to be known which has been proven is not the case in some of the simulated test cases. Figure 49 shows an example of a duration curve for export, generation and load on the left. On the right side of Figure 49, the same example is shown as a duration curve of net electricity export normalized with the designed grid connection capacity. The design generation, $\overline{G_{des}}$, and design load, $\overline{L_{des}}$, are represented in dotted lines.

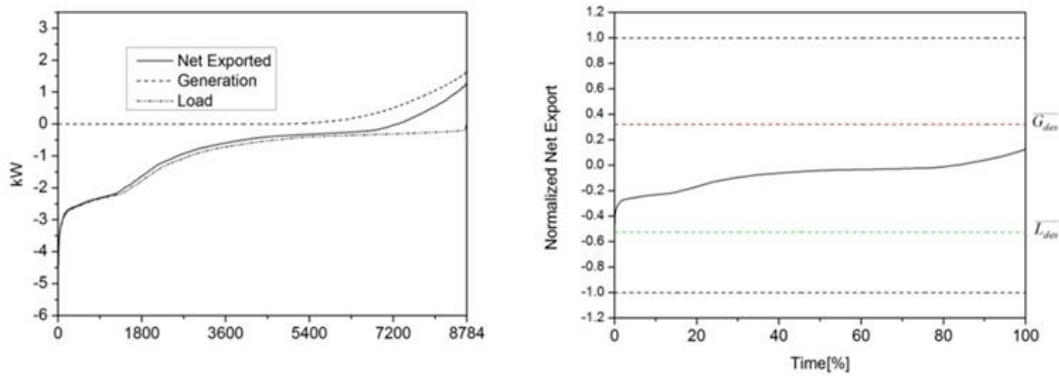


Figure 49: Example of duration curve for generation, load and net exported electricity (left) and Normalized net exported electricity duration curve (right). (Salom et al., 2014).

Coloured contour graphs (“carpet diagrams”) give a meaningful display of when and how much a building is importing or exporting energy over the year. Figure 50 shows a typical individual house with PV in a heating dominated climate on the left and a building with CHP on the right. The red end of the scales shows export. It is easy to see that the house with PV exports during daytime in the warmest months, whereas the CHP-building exports both day and night during the winter months when the heating demand is biggest (Salom et al., 2014). The same calculations can be done wind energy production.

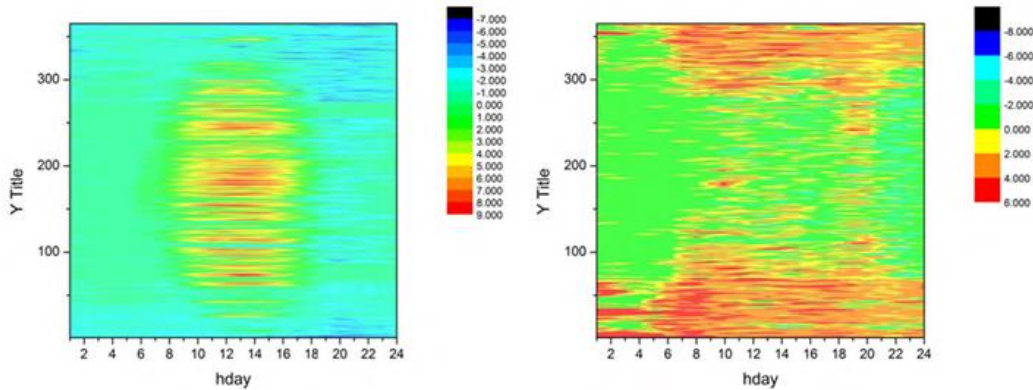


Figure 50: Example of coloured contour plots of net exported energy from a typical house with PV in a heating dominated climate (left) and similarly for a building with CHP generation on the right (Salom et al., 2014).

5.6 Institutional issues

5.6.1 "A paradoxical situation"

According to Karlstrøm and Ryghaug (2014), "Norway finds itself in a paradoxical situation regarding the role that new production of energy from renewable energy sources should play in the Norwegian energy system. On one hand, new types of renewable energy are far away from being competitive with the country's traditionally cheap main source of electricity and therefore need some sort of public support or subsidies in order to be realized. (...) On the other hand economists and others are claiming that Norway does not need more production of renewable energy as the domestic electricity demand has levelled out, the country is already more or less self-sufficient, and measures to enhance the production will in practice lead to subsidizing electricity production in Europe. (...) Thus, the Norwegian public is faced with a rather complex situation regarding what role new renewable energy technologies should and could play in the energy system" (Karlstrøm and Ryghaug, 2014).

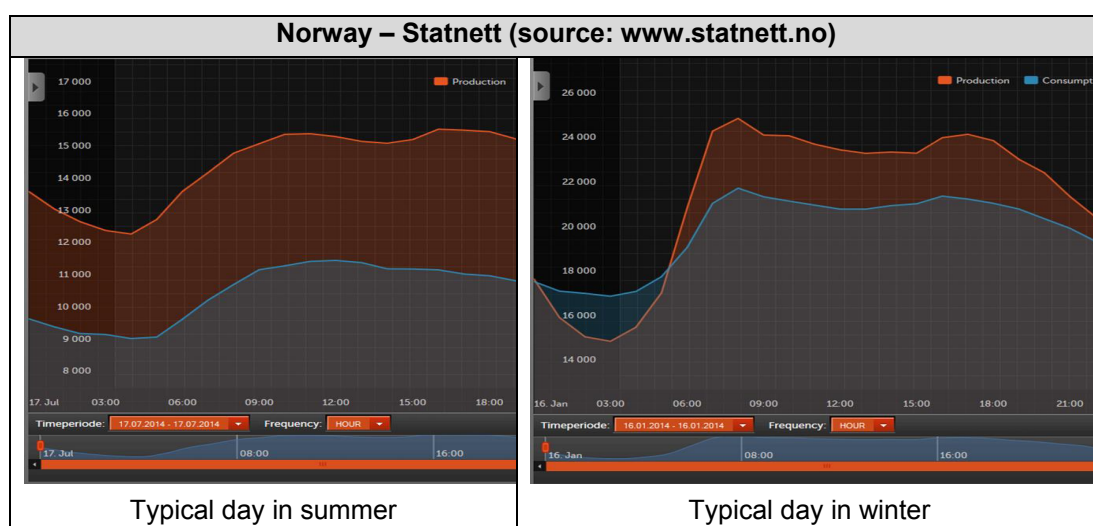


Figure 51: Electrical profiles for Norway (Statnett.no)

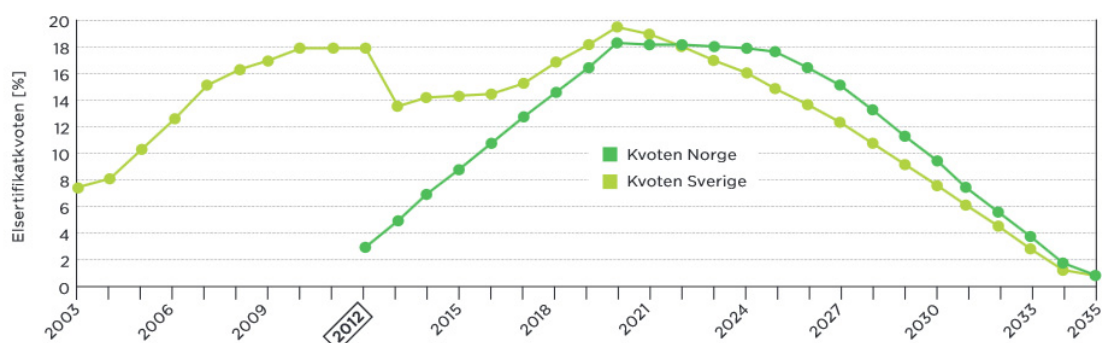
5.6.2 Electricity certificates

Since 1 January 2012, Sweden and Norway has a common market for electricity certificates. The common market is based on the Swedish electricity certificates - market that has existed since 2003. The goal is to increase renewable energy production by a total of 26.4 TWh in both countries from 2012 to 2020 and in this way contribute to countries' targets according to the EU renewables directive. This electricity certificate market is an example of a so-called cooperation mechanism under current EU renewables directive (Directive 2009/28/EC).

The EU renewables directive sets binding national targets for the share of renewable energy. It sets national binding targets to ensure that EU in 2020 should have a share of renewable energy of 20 percent of total energy use. To achieve the overall objective at the lowest cost it was opened to collaborate on initiatives through the so-called cooperation mechanisms, following four mechanisms defined in the Directive:

- (1) Renewable energy beyond what is needed to achieve its own goals can be sold (transferred statistically) from one member country to another.
- (2) joint energy projects in electricity, heating and cooling can be developed
- (3) for electricity it is also possible to collaborate on projects in third countries
- (4) two or more member states can coordinate support or establish joint support systems.

The Norwegian-Swedish electricity certificate scheme is an example of a common support system, and is the first example in the EU on how cooperative mechanisms can be utilized to achieve the national goals in 2020. Figure shows the past and future projected quotas that both Sweden and Norway have agreed upon. While in Sweden quotas for electricity certificates have increased from 8% (2003) to 18% (2012) Norway is expected to increase its quota from 3% (2012) to 18% (2020). Then both quotas are expected to decrease.



Figur 1. Kvotekurver for Sverige og Norge

Kilde: Lov (2011:1200) om elsertifikat; LOV 2011-06-24 nr 39: Lov om elsertifikater

Figure 52: Quotas for Sweden and Norway (Lov om elsertifikat)

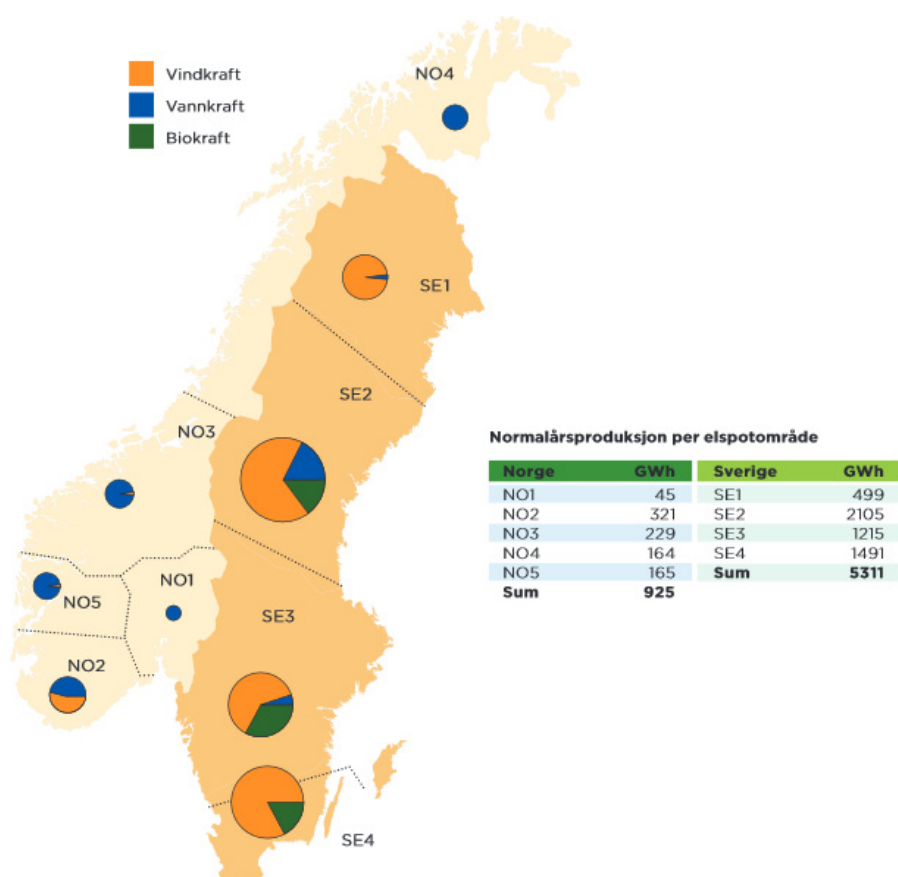


Figure 53: El-spot districts in Sweden and Norway normal year production for power plants contributing 26.4 TWh distributed over electricity certificate market (source: Energimyndigheten, NVE)

5.6.3 Other interesting developments

The NordLink project will connect the Norwegian and German electricity markets for the first time (Statnett).

The last couple of years have seen a significant increase in wind power and solar power in Germany. When the winds blow and the sun shines this creates a surplus of renewable energy in Germany, which also leads to lower prices than in Norway. Norway can then import this power and conserve the water in Norway's many hydropower reservoirs. When there is little production of wind power and solar power in Germany the need for power increases and the prices will be higher than in Norway. Norway can then produce hydropower and export it to Germany.

The advantages of this exchange of green energy include:

- Increased security of supply because one can import more electricity at a lower price when the power situation is tight
- Increased market for power producers when there is a surplus of power in the national markets
- Facilitation of higher production and consumption of renewable energy in Norway and Germany, thereby contributing to future climate-friendly energy
- More predictable supply situation and price throughout the year and from year to year

The investment decision for the project was taken on February 10th 2015, and the goal is to complete the project by 2019, followed by trial operations and commercial operations in 2020 (Statnett). This means that we are still in an evaluation phase and it is difficult to predict how this will develop further.

5.7 Conclusions

In order to integrate wind power efficiently at higher penetration levels, changes to the operating methods of various parts of the power system, such as generators and transmission systems, are required. Moreover, active management at the design side of the power system can be used to facilitate wind power integration. Wind power, with its variable output characteristics, affects other generators in the system. As well as reducing their required output, wind power also requires other plants in the system to be scheduled differently.

Grid interaction that monitors energy exchange between the building and the power grid can help to represent net exported energy in load duration curves. Delivered and exported peak values, amount of time when the building is exporting or demanding energy to or from the grid, period when the building is self-sufficient if a storage system is present, etc. can help to compare several renewable energy supply systems if this information is presented in a normalized form related to the connection capacity, together with information on extent of using the grid. This could be used to evaluate further benefits of connecting urban wind turbines to building load curves.

Since Norway has chosen to cooperate on meeting their renewable energy target of 67.5% by 2020 in a common green certificates scheme with Sweden, renewable energy installations will be deployed where it is most cost efficient to do so. Urban wind turbines have thus to be evaluated in feasibility studies and prove cost efficiency.

6 Conclusions and recommendations

A definition of building integrated wind turbines as well as building augmented wind turbines was provided. Building integrated wind turbines are integrated into the building with different levels of integration to distinguish. They can be integrated from the constructional point of view, from the architectural point of view and even from an electrical or energy point of view.

The most integrated wind turbines are augmented wind turbines that are defined as turbines that are specially designed for built environment, and can be located on buildings or on the ground next to buildings. The literature review revealed that there is a demand for inexpensive and efficient methods of predicting and collecting local wind data which was identified as a key driver for small wind turbines that requires further development and cost reduction.

One part of the study used questionnaire and qualitative interviews of house owners in order to find out more about their willingness to invest in wind power in the urban context as the market looks now. Another aim was to find out what are the issues that would be worth pursuing in relation to the future development and research on small building-augmented wind turbines in particular, but also in relation to local energy production in general. The results of the quantitative part of the study indicates that building augmented wind turbines would be well worth pursuing, but that noise levels should be a focus of attention in the further development of this technology. There is a general willingness to invest in this technology, and co-ownership with neighbours would be models worth pursuing in this context. Furthermore, the investment costs was not a major driver in relation to the willingness to invest in wind power.

The qualitative study revealed that aesthetic factors are of major influence and wind turbines were even considered aesthetically pleasing. Therefore, aesthetic factors should be specifically targeted in the further development of building augmented wind turbines as should its integration with the built environment.

Furthermore, the symbolic values of wind power and its combinability with solar power should be investigated further. Different ownership models and especially co-ownership should be specifically investigated. In addition, the technology might be more relevant in relation to summer houses than for the urban environment. However, this may well change once small scale building augmented wind turbines of different models and placement on the the buildings have been developed, especially since aesthetic factors were considered important in relation to wind power in general.

A parametric analysis was undertaken in order to get a better understanding of the parameters that influence the effectiveness of urban wind turbines. This study considered the following parameters:

- wind turbine type
- axis height
- turbine area
- surrounding topography
- wind channeling effect

The effect of location is very important, together with turbine size type and size. Different turbine types have different power coefficients which influence the number of rotors needed for same wind profiles. Turbine size is of course beneficial but larger turbines become more difficult to integrate into the buildt environment.

The wind profiles can also be influenced by designers and planners by taking urban and building design in to account and specifically focusing on the parameters axis height, surrounding topography and wind channeling effect. The axis height is strongly linked to the building geometry and especially height as a restricting parameter. A large potential can be found for wind channeling effects which is most prominent in situations where the building design is augmented to increase wind velocities. Due to the rough assumptions the channeling effect might also be overestimated in these calculations. More detailed flow simulation work is needed to be able to draw final conclusions.

The results provide useful information for designers and planners of small urban wind turbines. It should not be used to read exact energy production but rather to get an idea and to compare the importance of each parameter. It will still be obligatory to make detailed energy calculations before planning and projecting a wind turbine.

In order to integrate wind power efficiently at higher penetration levels, changes to the operating methods of various parts of the power system, such as generators and transmission systems, are required. Moreover, active management at the design side of the power system can be used to facilitate wind power integration. Wind power, with its variable output characteristics, will affect other generators in the system. As well as reducing their required output, wind power also requires other plants in the system to be scheduled differently.

Grid interaction that monitors energy exchange between the building and the power grid can help to represent net exported energy in load duration curves. Delivered and exported peak values, amount of time when the building is exporting or demanding energy to or from the grid, period when the building is self-sufficient if a storage system is present, etc. can help to compare several renewable energy supply systems if this information is presented in a normalized form related to the connection capacity, together with information on extent of using the grid. This could be used to evaluate further benefits of connecting urban wind turbines to building load curves.

Since Norway has chosen to cooperate on meeting their renewable energy target of 67.5% by 2020 in a common green certificates scheme with Sweden, renewable energy installations will be deployed where it is most cost efficient to do so. Urban wind turbines have thus to be evaluated in feasibility studies and prove cost efficiency. The parametric study revealed the most important factors when determining the efficiency of wind turbines. It became clear that wind turbines in unobstructed areas are much more efficient. There must be other (additional) reasons for the decision if and where to apply wind turbines in the built environment. The user acceptance study revealed that aesthetic factors were considered important in relation to wind power in general as well as noise issues.

More work is needed when it comes to harvesting the full potential of building augmented wind turbines. The integration of wind turbines in buildings poses a number of issues regarding noise and vibration. The development of the technology needs to address these issues carefully. However, there seems to be a positive image connected to wind turbines. This should be further exploited. The augmentation of buildings needs careful design and advanced simulation together with wind tunnel tests are recommended. The examples show rather large building projects and the application and further development for small houses should be further investigated.

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Wieringa, J. (1981). Estimation of Mesoscale and Local-Scale Roughness for Atmospheric Transport deling. In C. de Wispelaere (ed.). *Air Pollution Modeling and its Application*. New York: Plenum, pp. 279-295.

Figures references

Figure	Title	Reference
1	Typical configurations for horizontal and vertical axis wind turbines	www.daviddarling.info
2	Roof mounted wind turbines	Clock-wise from top left: © Andy Wright, Wikimedia Commons File:Co-operative Insurance Manchester 252753059.jpg - Wikimedia Commons www.solarhighway.org cleantechnica.com http://www.greenmagonline.com/wp-content/uploads/2010/09/ArchWindmain-web.jpg
3	Vertical axis wind turbines, roof mounted	Left: www.renewableenergyfocus.com Right: ©SINTEF Building and Infrastructure
4	Building integrated wind turbine, horizontal axis (Strata SE 1, London)	Left: "Strata SE1 from Monument 2014", © Colin / Wikimedia Commons, https://en.wikipedia.org/wiki/Strata_SE1 Right: © Gordon Haws, Flickr
5	Building integrated wind turbines with vertical axis (Public utility commission HQ, San Francisco)	Left: Images and/or Video Courtesy of the San Francisco Public Utilities Commission/Photographer Robin Scheswohl Right:© Ute Poerschke, The Pennsylvania State University, Department of Architecture See also: http://wind.psu.edu/building-integrated-wind-energy/database
6	Building augmented wind turbine, horizontal axis (World Trade Center, Bahrain)	Left: Blog, Susanna Saghatelian, http://mosticonicskyscrapers.blogspot.no/2012/08/13-bahrain-world-trade-center-manama.html , Right: © abcdz2000, Flickr See also http://www.atkinsglobal.com/en-GB/projects/bahrain-world-trade-center
7	Building augmented wind turbine (vertical axis) (Greenway Self Park, Chicago, USA)	© John Picken See also: http://www.architectmagazine.com/technology/detail/integrated-wind-turbine_o http://www.hok.com/design/type/commercial/greenway-self-park/
8	Building augmented wind turbine (vertical axis) (Kinetica, Dalston,	© Waugh Thistleton Architects, http://www.waughthistleton.com/favicon.ico See also:

Figure	Title	Reference
	London)	http://www.wind.psu.edu/buildings/kinetica.asp
9	Building augmented wind turbine (vertical axis) (Pearl River Tower, Guangzhou, China)	© Both pictures: Si-ye Zhang Se also: http://www.wind.psu.edu/buildings/guangzhou.asp http://www.som.com/projects/pearl_river_tower http://skyscrapercenter.com/building/pearl-river-tower/454 http://inhabitat.com/worlds-greenest-skyscraper-pearl-river-tower-almost-complete/
10	Monthly wind velocities of different measurement stations	(Haase and Skeie, 2015)
11	Flow categories with typical density of terrain obstacles and indication of appropriate wind profile shapes	(Wieringa, 1981)
12	Channeling effect of the Tobacco tower in Guangzhou	https://thewaywelive.wordpress.com/2007/03/26/building-integrated-wind-turbines/
13	Channeling effect of the World Trade Center in Bahrain (under two different wind directions)	http://flowsquare.com/2014/05/15/bahrain-world-trade-centre/
14	Plan Area Density (roughness R in meters)	(CPCALC, Grosso 1992)
15	Surrounding building height S_bH	(Grosso 1992)
16	Monthly wind velocities measured and adjusted for height and terrain	© SINTEF Building and Infrastructure
17	General blade design	computationalnonlinear.asmedigitalcollection.asme.org
18	Power coefficients of different rotor types in relation to TSR (λ)	(Hau, 2000)
19-44	various	SINTEF Building and Infrastructure
45	Monthly end-use electricity consumption and	(NVE, 2011).

Figure	Title	Reference
	the average system price on the Nordpool market in EUR/MWh	
46	Example of load cover factors (right) and supply cover factors (left) represented as mean values for four months	(Salom et al., 2014)
47	Example of duration curve for generation, load and net exported electricity (left) and Normalized net exported electricity duration curve (right).	(Salom et al., 2014)
48	Example of coloured contour plots of net exported energy from a typical house with PV in a heating dominated climate (left) and similarly for a building with CHP generation on the right	(Salom et al., 2014)
49	Electrical profiles for Norway	www.statnett.no
50	Quotas for Sweden and Norway	Lov om elsertifikat
51	El-spot districts in Sweden and Norway normal year production for power plants contributing 26.4 TWh distributed over electricity certificate market	Energimyndigheten, NVE

Appendix

List of contents of appendices

- A: Questionnaire
- B: Questionnaire answers
- C: Blade design
- D: Plans
- E: Projects
- F: Wind data

A Questionnaire

The original Questionnaire contained some photos that we have edited out here to focus only on the questions. The questionnaire was also used as interview guide.

Bygningsintegrerte vindmøller

Bakgrunnen for prosjektet er nye små vindmøller som kan integreres med bygninger. Dette muliggjør lokal produksjon av fornybar energi for hus og huseiere, både separat og i samarbeid med naboer.

Vi er interessert i å finne ut under hvilke omstendigheter du vil vurdere å installere/investere i slik teknologi. Vi er interessert i å finne ut hvilke temaer som er viktigst for deg i forhold til små vindmøller for bygninger og i forhold til lokal produksjon av energi generelt.

Spørreskjemaet tar ca. 8 minutter å gjennomføre. Resultatet vil bli brukt som del av et forskningsprosjekt og vi er veldig takknemlige for din deltagelse.

Hvilken type bygg eier/forvalter du?

Check all that apply.

- ☐ Eier enebolig
- ☐ Eier bolig i flerbolighus
- ☐ Eier/forvalter av flerbolighus
- ☐ Eiere av næringsbygg
- ☐ Other:

This is a required question

Hva er din generelle holdning til vindmøller?

Vi tenker da på de vi typisk finner i landskapet i dag

Mark only one oval.

1 2 3 4 5

Veldig negativ ☐ ☐ ☐ ☐ ☐ Veldig positiv

This is a required question

Hvordan tror du du ville oppleve at tradisjonelle vindmøller ble installert nær der du bor? Mark only one oval.

1 2 3 4 5

Veldig negativ ☐ ☐ ☐ ☐ ☐ Veldig positiv

This is a required question

Hva er din generelle holdning til småskala vindmøller integrert i bygninger?

Mark only one oval.

1 2 3 4 5

Veldig negativ ☐ ☐ ☐ ☐ ☐ Veldig positiv

This is a required question

Hvordan tror du du ville oppleve at nye små vindmøller ble installert på ditt hus eller nær der du bor?

Mark only one oval.

- ☐ ☐ Jeg ville aktivt prøve å motvirke det
- ☐ ☐ Jeg ville ikke like det, og kunne kanskje komme til å protestere
- ☐ ☐ Jeg ville akseptere det, men være skeptisk
- ☐ ☐ Jeg ville akseptere det og være positiv
- ☐ ☐ Jeg ville like det
- ☐ ☐ Jeg ville engasjere meg aktivt og prøve å få det til å skje
- ☐ ☐ Other:

This is a required question

Energieffektivitet: Tror du små vindmøller på bygninger er energieffektive eller ikke?

Mark only one oval.

1 2 3 4 5

Veldig lite effektive ☐ ☐ ☐ ☐ ☐ Veldig effektive

This is a required question

Hvor viktig er energieffektivitet for deg?

Mark only one oval.

1 2 3 4 5

Ikke viktig i det hele tatt ☐ ☐ ☐ ☐ ☐ Veldig viktig

This is a required question

Sikkerhet: Tror du små vindmøller på bygninger er sikre eller ikke?

Med sikkerhet mener vi risikofaktorer som f.eks. ulykker

Mark only one oval.

1 2 3 4 5

Veldig lav sikkerhet ☐ ☐ ☐ ☐ ☐ Veldig høy sikkerhet

This is a required question

Hvor viktig er sikkerhet for deg?

Mark only one oval.

1 2 3 4 5

Ikke viktig i det hele tatt ☐ ☐ ☐ ☐ ☐ Veldig viktig

This is a required question

Bærekraftighet: Tror du små vindmøller på bygninger er bærekraftige?

Mark only one oval.

1 2 3 4 5

Veldig lite bærekraftig ☐ ☐ ☐ ☐ ☐ Veldig bærekraftig

This is a required question

Hvor viktig er bærekraft for deg?

Mark only one oval.

1 2 3 4 5

Ikke viktig i det hele tatt ☐ ☐ ☐ ☐ ☐ Veldig viktig

This is a required question

Vedlikehold: Tror du små vindmøller på bygninger krever mye vedlikehold?

Mark only one oval.

1 2 3 4 5

Veldig lite vedlikehold ☐ ☐ ☐ ☐ ☐ Veldig mye vedlikehold

This is a required question

Hvor viktig er behovet for vedlikehold for deg?

Mark only one oval.

1 2 3 4 5

Veldig lite viktig ☐ ☐ ☐ ☐ ☐ Veldig viktig

This is a required question

Støy: Tror du små vindmøller på bygninger skaper mye støy?

Mark only one oval.

1 2 3 4 5

Veldig lite støy ☐ ☐ ☐ ☐ ☐ Veldig mye støy

This is a required question

Hvor viktig er støynivået for deg?

Mark only one oval.

1 2 3 4 5

Ikke viktig i det hele tatt ☐ ☐ ☐ ☐ ☐ Veldig viktig

This is a required question

Delt eierskap til vindmøller har blitt en suksess bl.a. i Danmark. Ville du være interessert i å være deleier i en vindmølle sammen med dine naboer?

Mark only one oval.

1 2 3 4 5

Ikke interessert ☐ ☐ ☐ ☐ ☐ Veldig interessert

This is a required question

Ville du være interessert i å investere i eller installere en liten vindmølle på din eiendom?

Mark only one oval.

1 2 3 4 5

Ikke interessert ☐ ☐ ☐ ☐ ☐ Veldig interessert

This is a required question

Økonomi: Hvor kostbar tror du investering i vindkraft er i forhold till annen strømproduksjon?

Mark only one oval.

1 2 3 4 5

Veldig dårlig investering ☐ ☐ ☐ ☐ ☐ Veldig god investering

This is a required question

Har du noen kommentarer i forhold til det å investere i vindkraft?

This is a required question

Hvordan forholder du deg til vindmøller på ditt eget tak?

Mark only one oval.

1 2 3 4 5

Veldig negativ ☐ ☐ ☐ ☐ ☐ veldig positiv

This is a required question

Hvordan forholder du deg til vindmøller installert på fasaden av din bygning?

Mark only one oval.

1 2 3 4 5

Veldig negativ ☐ ☐ ☐ ☐ ☐ Veldig positiv

This is a required question

Har du noen kommentarer i forhold til vindmøller på fasaden?

This is a required question

Bør vindmøller være skjult eller synlige / del av bygningens form?

Check all that apply.

- ☐ Skjult
- ☐ Synlige

This is a required question

Illustrasjonsbilde: Bygningsintegreerte vindmøller i hjørne på fasade

This is a required question

Vennligst gi oss dine personlige kommentarer om vindmøller. Vi vil gjerne lese.

Submit

100%: You made it.

Never submit passwords through Google Forms.

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This content is neither created nor endorsed by Google.

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[Edit this form](#)

B Questionnaire answers

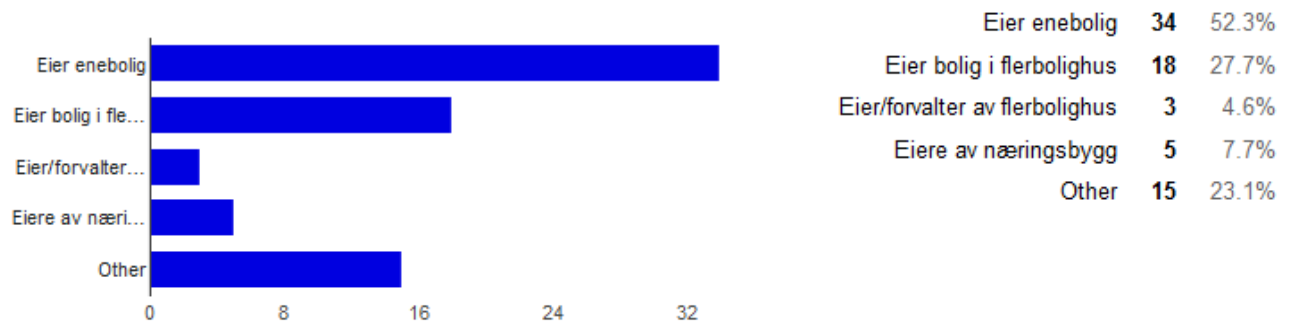


Figure B.1 – Spørsmål 1: Hvilken type bygg eier/forvalter du?

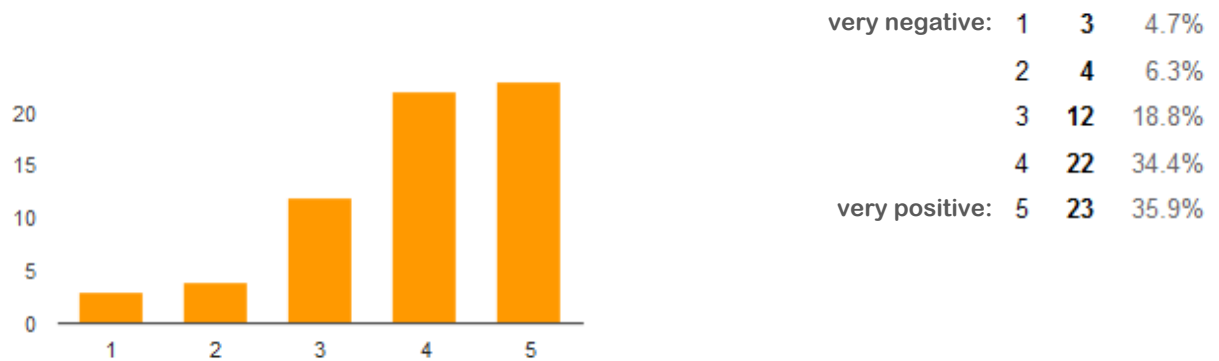


Figure B.2 – Question 2: What is your general impression of Wind turbines?

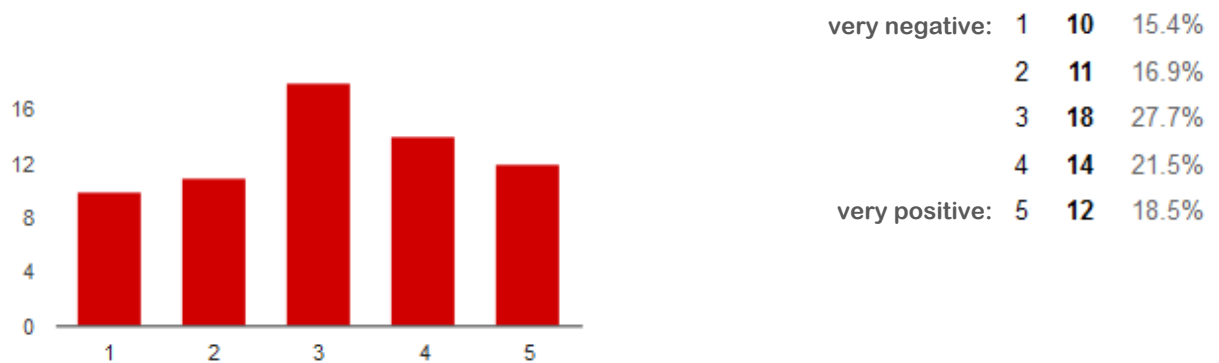


Figure B.3 – Question 3: How would you feel about traditional wind turbines being installed in your near vicinity (specify distance)?

Hva er din generelle holdning til småskala vindmøller integrert i bygninger?

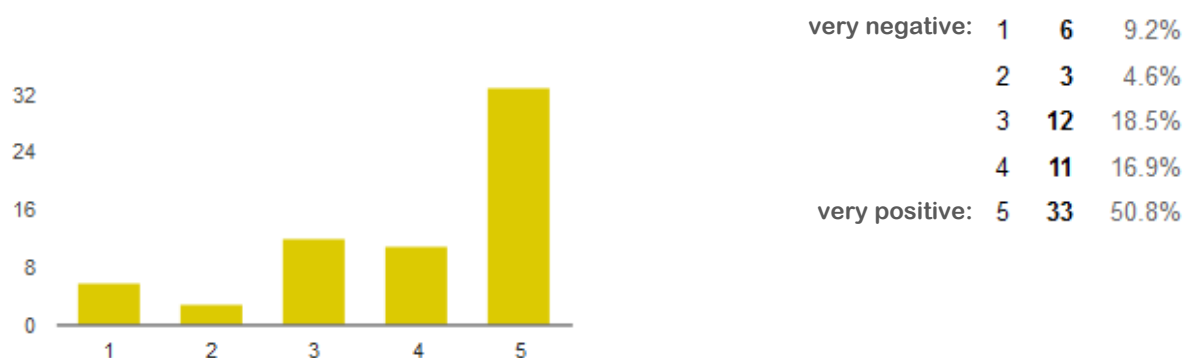


Figure B.4 – Question 4: What is your general impression of smaller wind turbines as an integrated part of the built environment?

Hvordan tror du du ville oppleve at nye små vindmøller ble installert på ditt hus eller nær der du bor?



Figure B.5 – Question 5: How would you feel about new smaller wind turbines being installed in your near vicinity/on your building (specify distance)?

Energieffektivitet: Tror du små vindmøller på bygninger er energieffektive eller ikke?

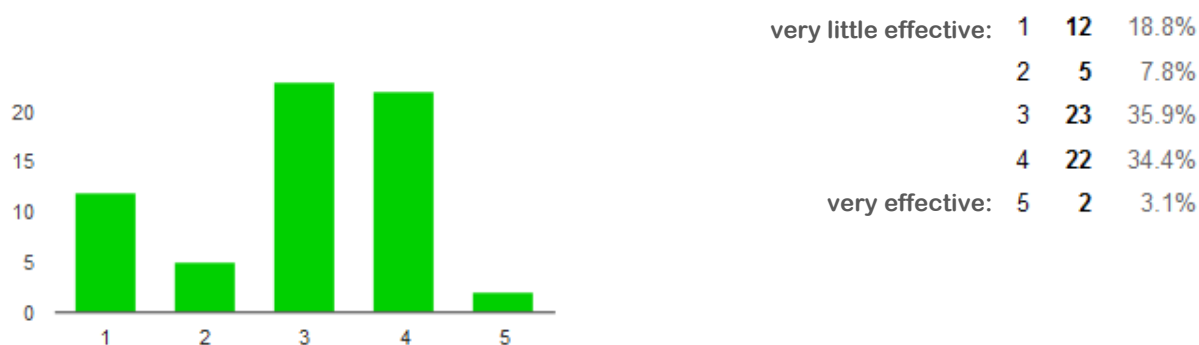


Figure B.6 – Question 6: Energy Efficiency: How would you value your impression of smaller building augmented wind turbines in relation to energy efficiency?

Hvor vigtig er energieffektivitet for deg?

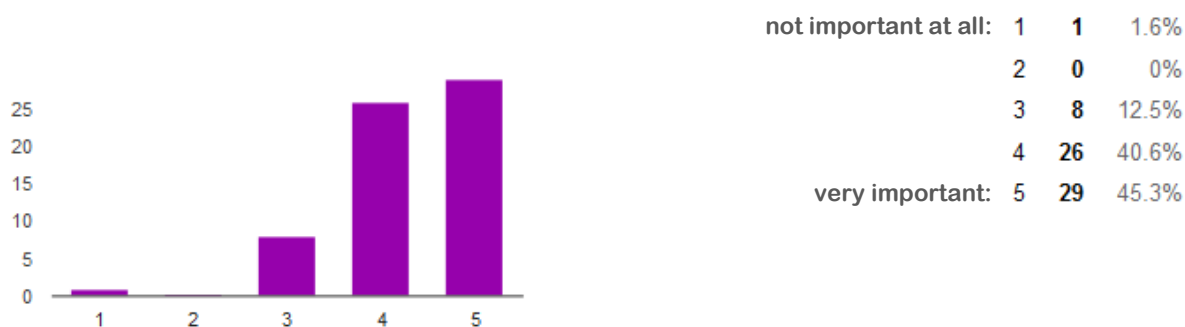


Figure B.7 – Question 7: How important is this factor (energy efficiency)?

Sikkerhet: Tror du små vindmøller på bygninger er sikre eller ikke?

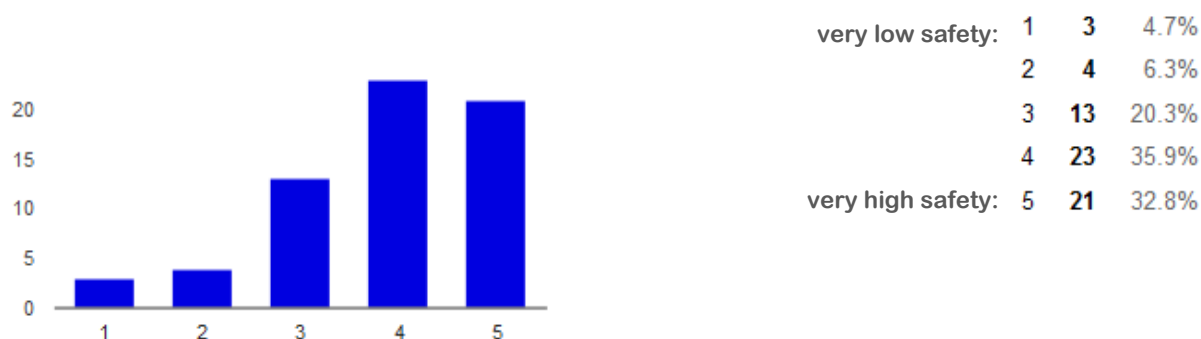


Figure B.8 – Question 8: How would you value your impression of smaller building augmented wind turbines in relation to safety?

Hvor vigtig er sikkerhet for deg?

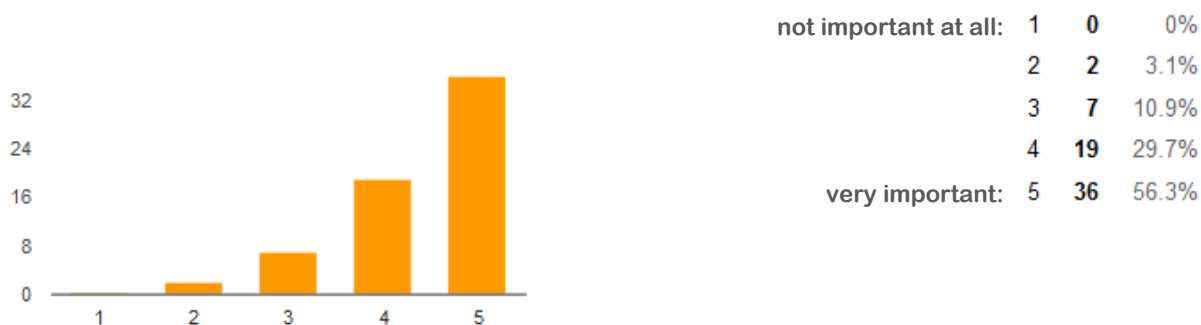


Figure B.9 – Question 9: How important is this factor (safety)?

Bærekraftighet: Tror du små vindmøller på bygninger er bærekraftige?

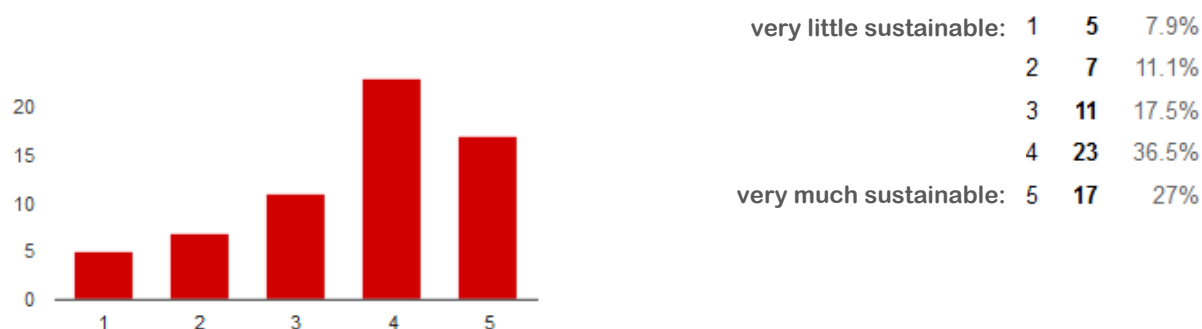


Figure B.10 – Question 10: How would you value your impression of smaller building augmented wind turbines in relation to sustainability?

Hvor viktig er bærekraft for deg?

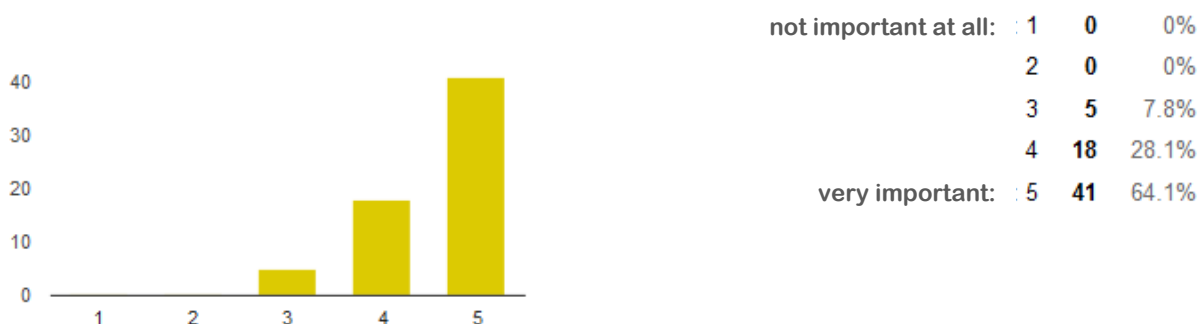


Figure B.11 – Question 11: How important is this factor (sustainability)?

Vedlikehold: Tror du små vindmøller på bygninger krever mye vedlikehold?

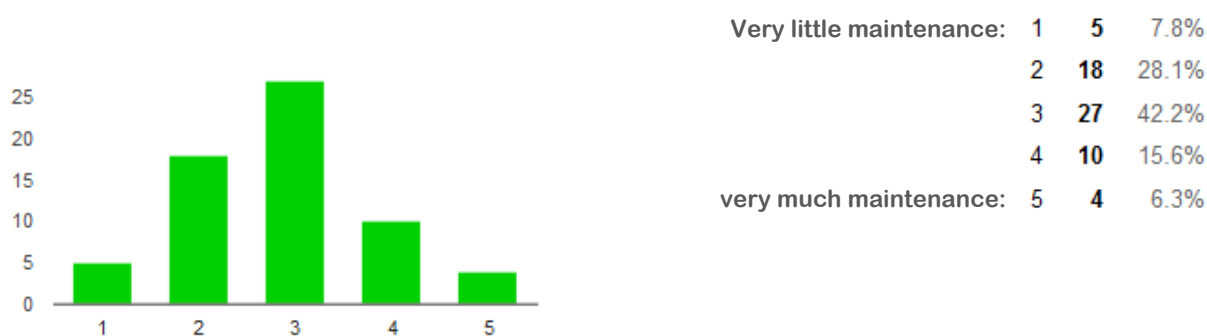
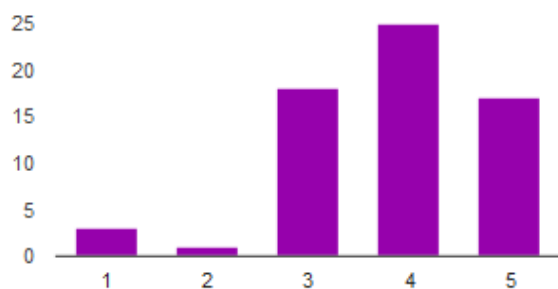


Figure B.12 – Question 12: How would you value your impression of smaller building augmented wind turbines in relation to long-term maintenance costs?

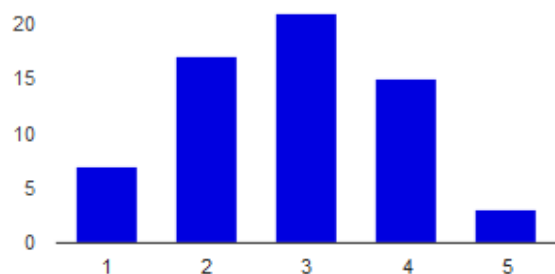
Hvor viktig er behovet for vedlikehold for deg?



not important at all:	1	3	4.7%
	2	1	1.6%
	3	18	28.1%
very important:	4	25	39.1%
	5	17	26.6%

Figure B.13 – Question 13: How important is this factor (long-term maintenance costs)?

Støy: Tror du små vindmøller på bygninger skaper mye støy?

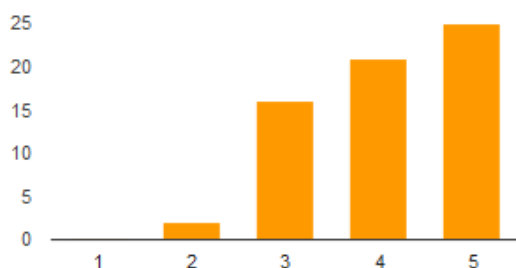


Very low noise levels:	1	7	11.1%
	2	17	27%
	3	21	33.3%
very high noise levels:	4	15	23.8%
	5	3	4.8%

Figure B.14 – Question 14: How would you value your impression of smaller building augmented wind turbines in relation to noise levels?

Noise level was considered an important factor, and this seems to be an issue of concern in relation to small wind turbines on buildings.

Hvor viktig er støynivået for deg?



not important at all:	1	0	0%
	2	2	3.1%
	3	16	25%
very important:	4	21	32.8%
	5	25	39.1%

Figure B.15 – Question 15: How important is this factor (noise levels)?

Delt eierskap til vindmøller har blitt en suksess bl.a. i Danmark.

Ville du være interessert i å være deleier i en vindmølle sammen med dine naboer?

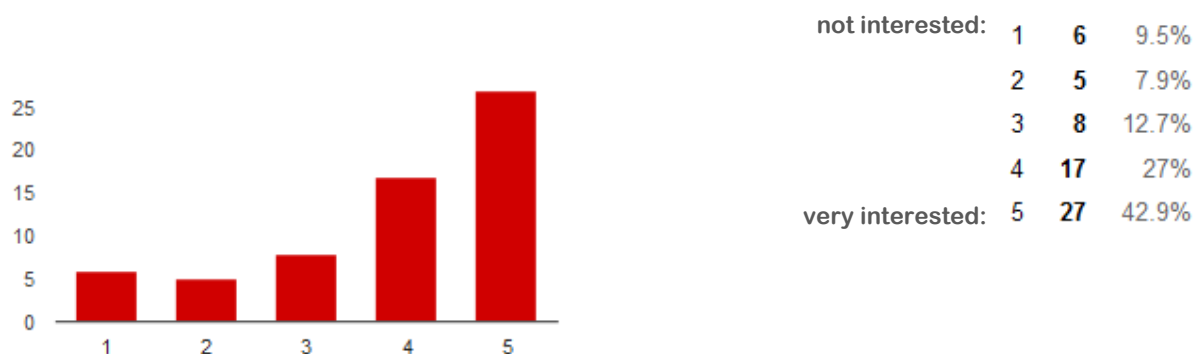


Figure B.16 – Question 16: Shared ownership of wind turbines has been a success in for instance Denmark. Would you be interested in co-owning a small-scale wind turbine together with your neighbors?

Ville du være interessert i å investere i eller installere en liten vindmølle på din eiendom?

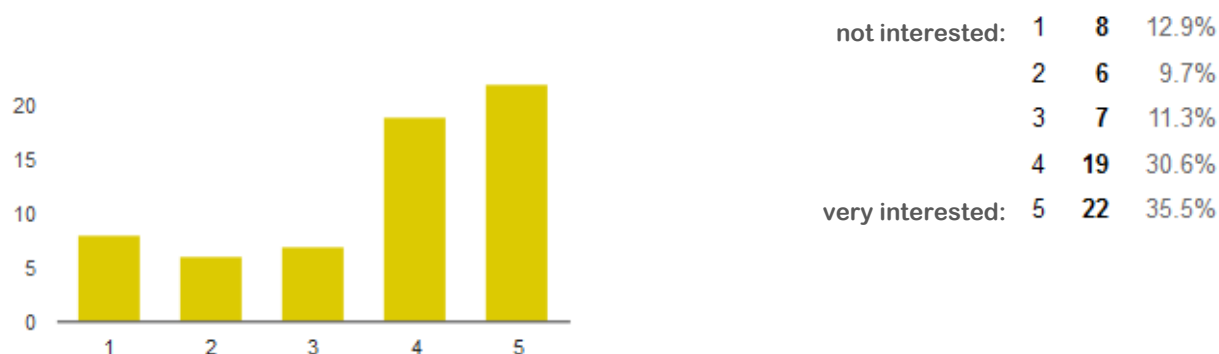


Figure B.17 – Question 17: Would you be interested in investing in/installing a small-scale wind turbine as part of your property?

Økonomi: Hvor kostbar tror du investering i vindkraft er i forhold till annen strømproduksjon?

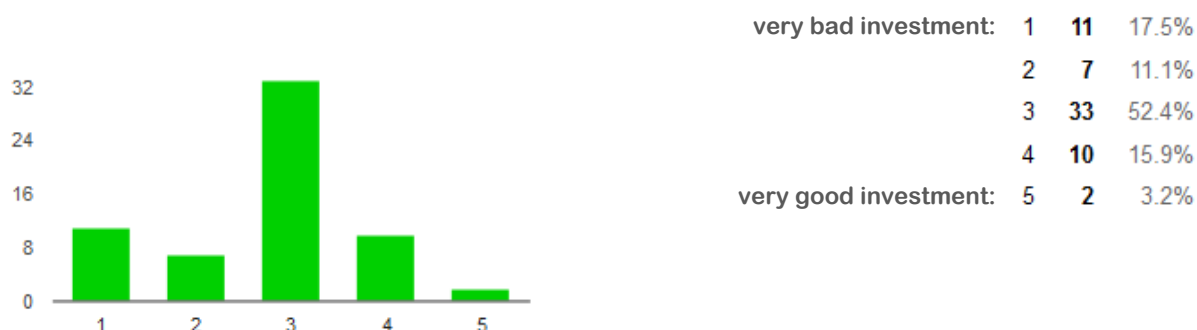


Figure B.18 – Question 18: Do you have any comments related to investing in wind power?

Hvordan forholder du deg til vindmøller på ditt eget tak?

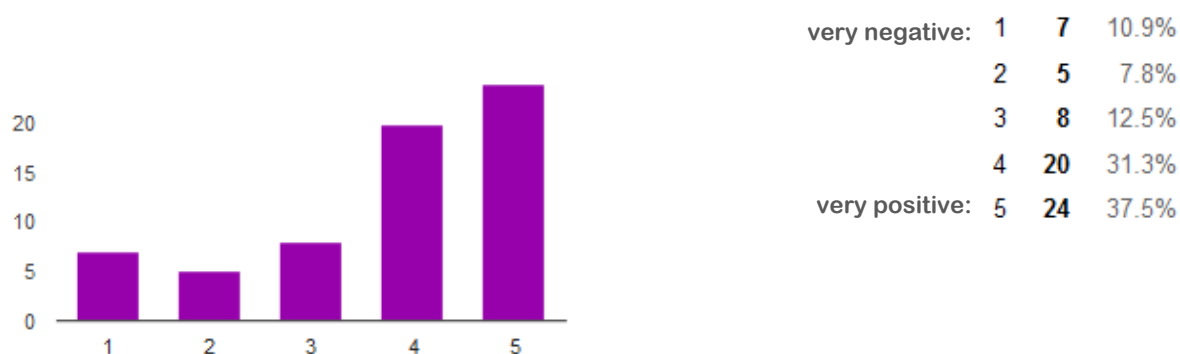


Figure B.19 – Question 19: How would you feel about having wind turbines installed on your roof?

Hvordan forholder du deg til vindmøller installert på fasaden av din bygning?

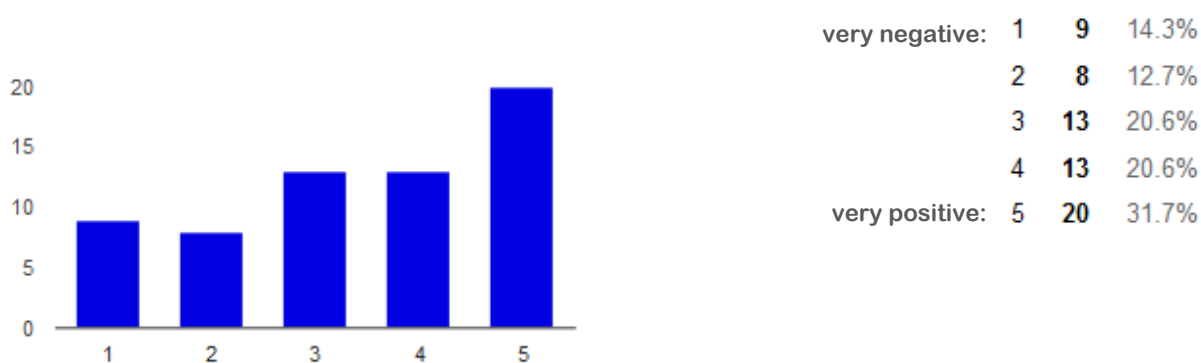


Figure B.20 – Question 20: How would you feel about having wind turbines installed on the facade/building (corners)?

Bør vindmøller være skult eller synlige / del av bygningens form?



Figure B.21 – Question 21: Should wind turbines be hidden or visible, made part of the building shape?

C Blade design

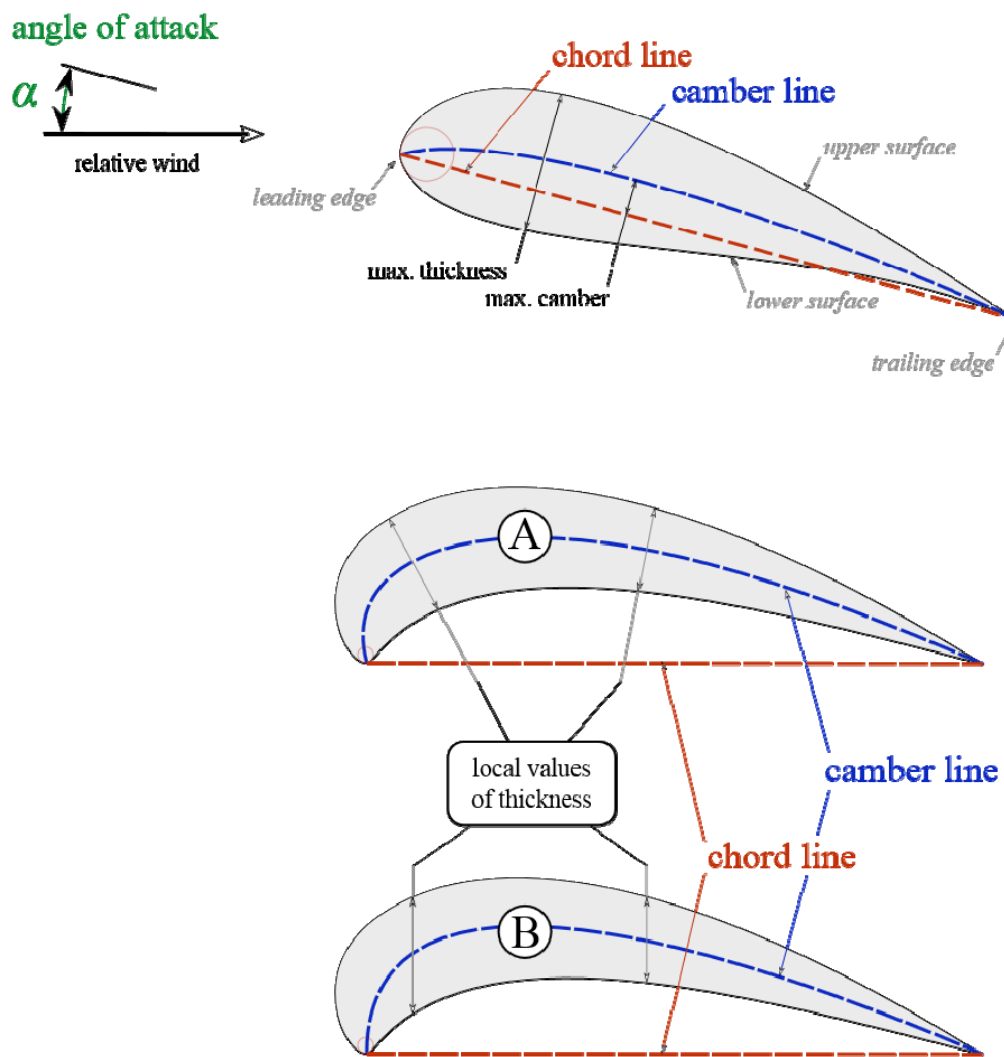


Figure C1: wing geometry definitions (A), (B)
(computationalnonlinear.asmedigitalcollection.asme.org)

D Plans

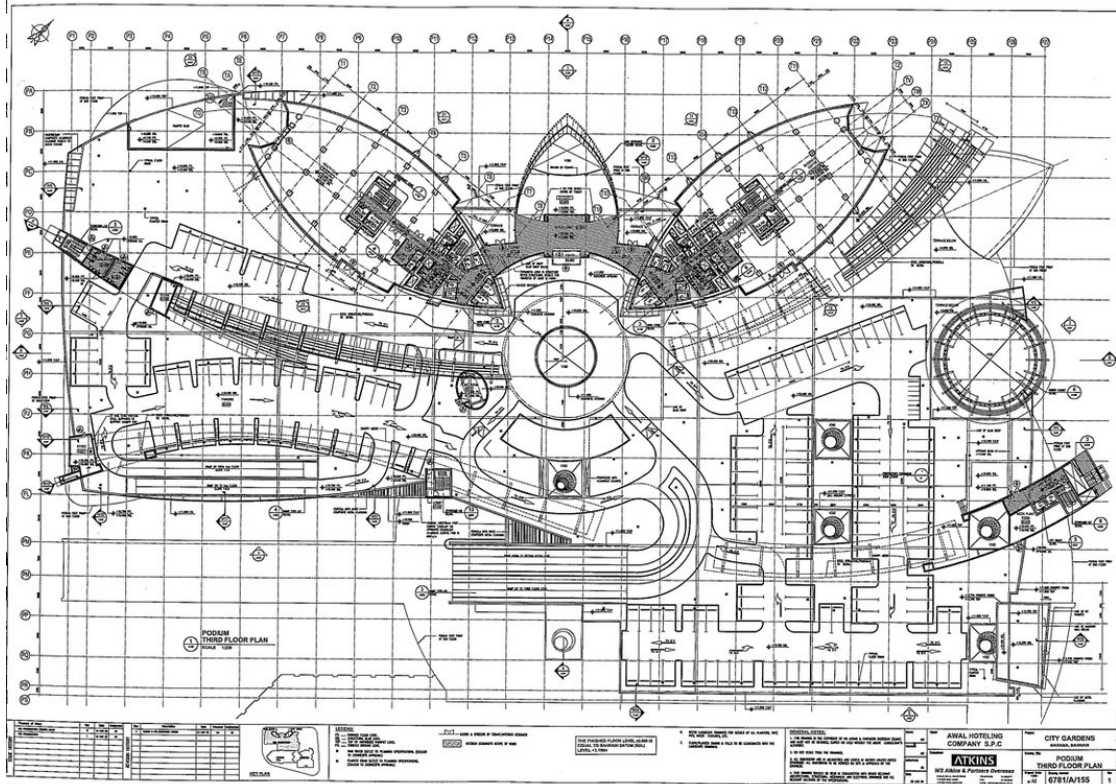


Figure D1: Plan of Bahrain World Trade Center

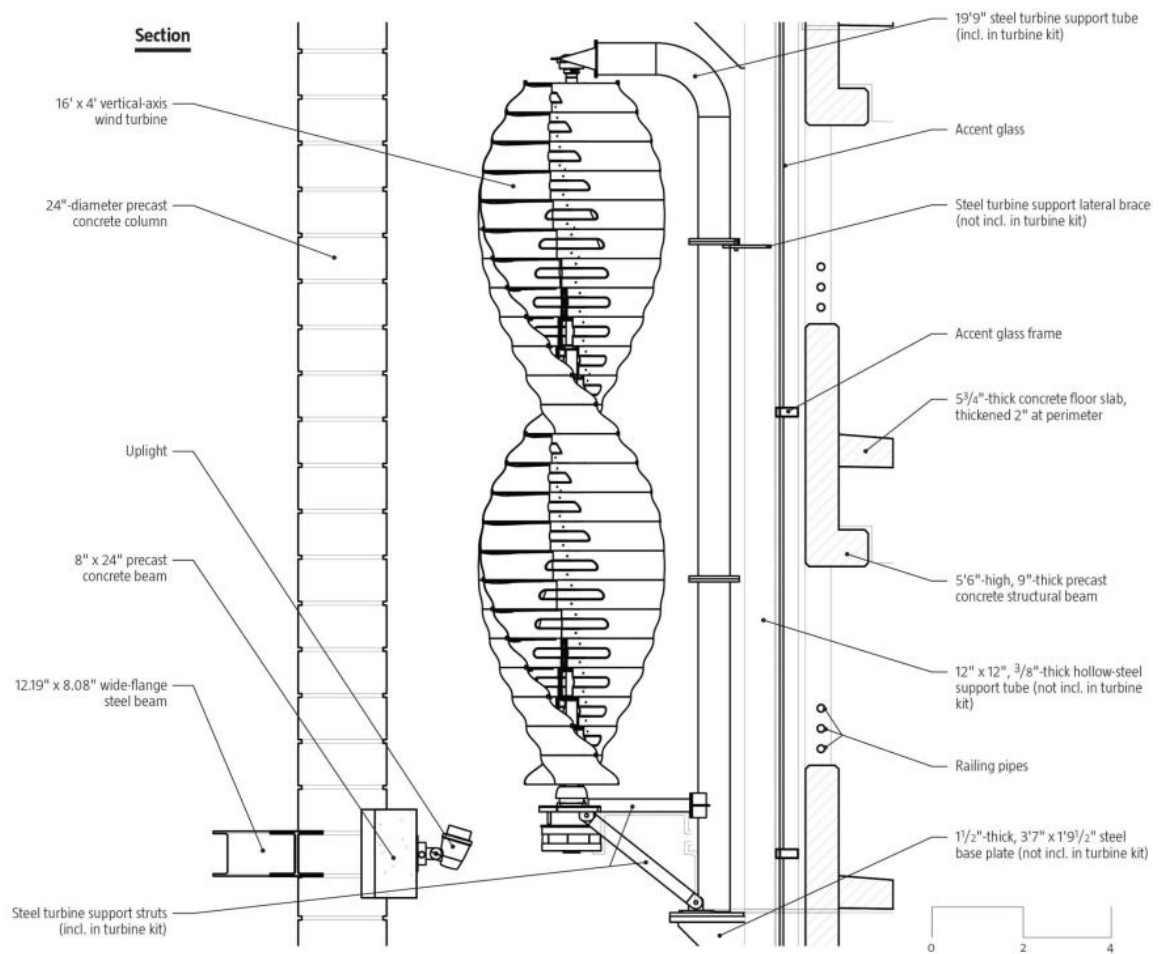


Figure D2: http://www.architectmagazine.com/technology/detail/integrated-wind-turbine_o

E Projects

Name	Description	Picture
Bahrain World Trade Center (also called Bahrain WTC or BWTC)	Location: Manama, Bahrain Year of completion: 2008 Use: administration Scale: highrise Architects: Atkins Wind turbine product: 3 turbines, 225kW each, Ø 29m Photo, © abcdz2000	
Greenway Self Park, Chicago, USA	Location: W Kinzle St/Clarke St, Chicago, IL 60654, USA Year of completion: 2009 Use: parking Scale: 11 floors Architects: HOK Turbines: 12 Helix Wind S594 turbines Reference: Gidion Fink Shapiro, Integrated Wind Turbine, in: Architect Magazine of AIA, December 2010	

**Kinetica,
Dalston,
London**

Location:
Dalston,
London E8, UK
Year of
Completion:
2009
Use: mixed-
use
(residential,
offices)
Scale: 14
floors
Architects:
Waugh
Thistleton
Wind turbine:
Quiet
Revolution



**Pearl River
Tower,
Guangzhou,
China**

Architect:
Skidmore,
Owens,
Merrell (SOM)
Completion
Year:
2009/2010
Site Area:
10,635 m²
Project Area:
212,165 m²
Building
Height:
309.60 m
Number of
Stories: 71
4 vertical axis
wind turbines



**Strata SE 1,
London**

Location: 8
Walworth Rd,
Southwark,
London, SE1,
UK
Year of
completion:
2010
Use:
residential
Scale: 43
floors, 148m
Architects:
BFLS
Engineers:
WFL Group
Combined
capacity of
turbines:
57kW



**Public
utility
commission
HQ**

Location: 525
Golden Gate,
San Francisco,
CA, USA
Year of
completion:
2012
Use:
administration
Scale: highrise
(13 floors)
Architects:
KMD, Stevens,
JV



F Wind data

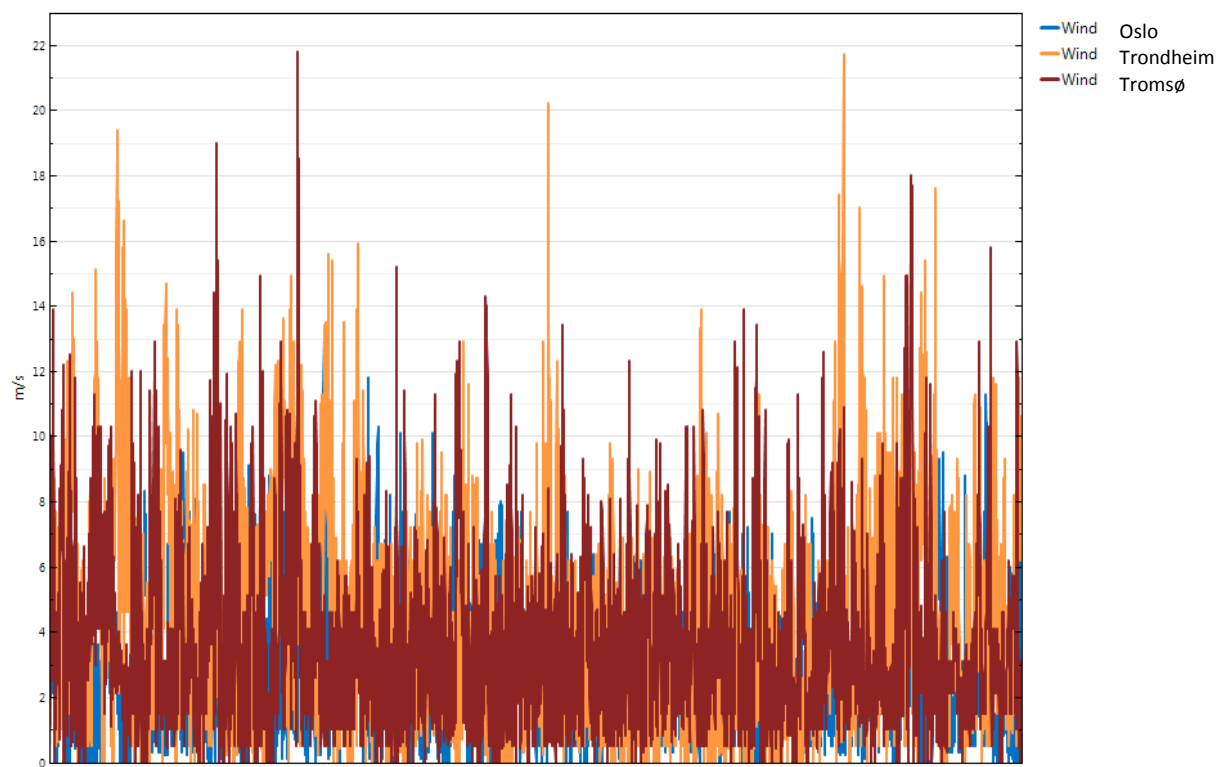


Figure F.1: Hourly data

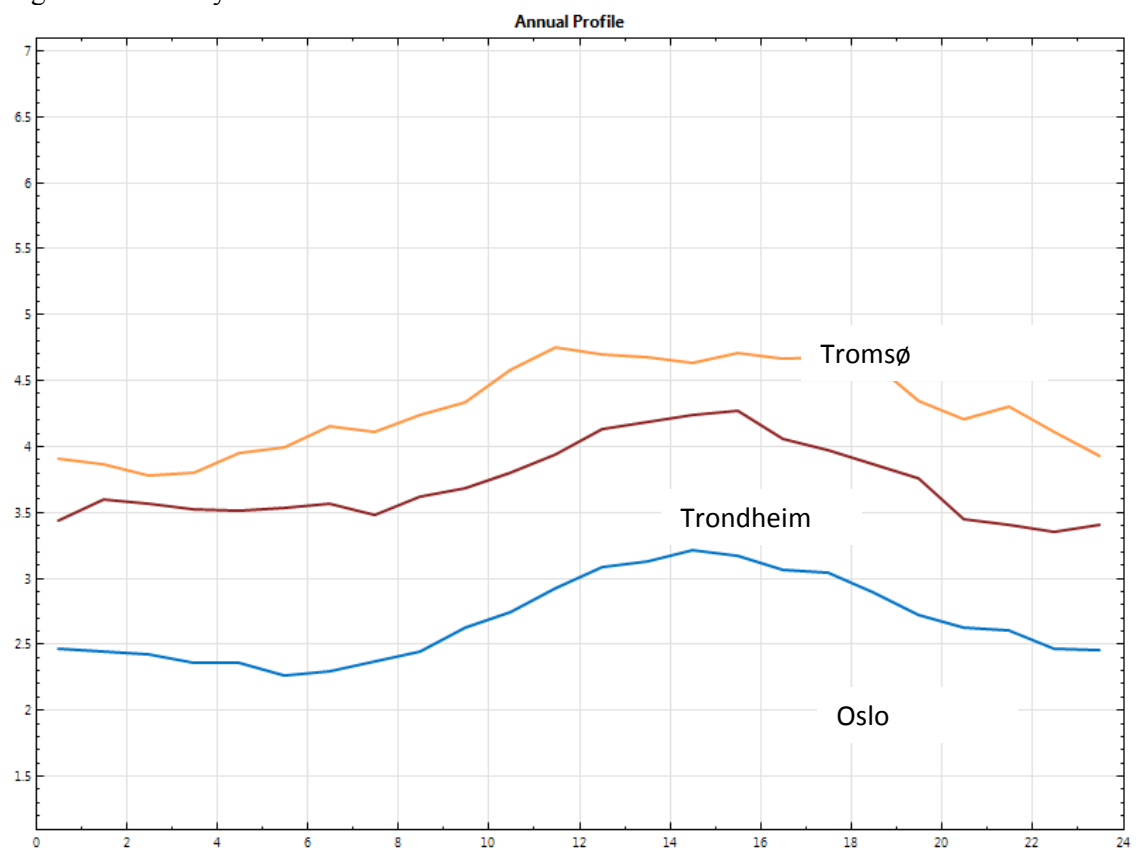


Figure F.2: Annual profile

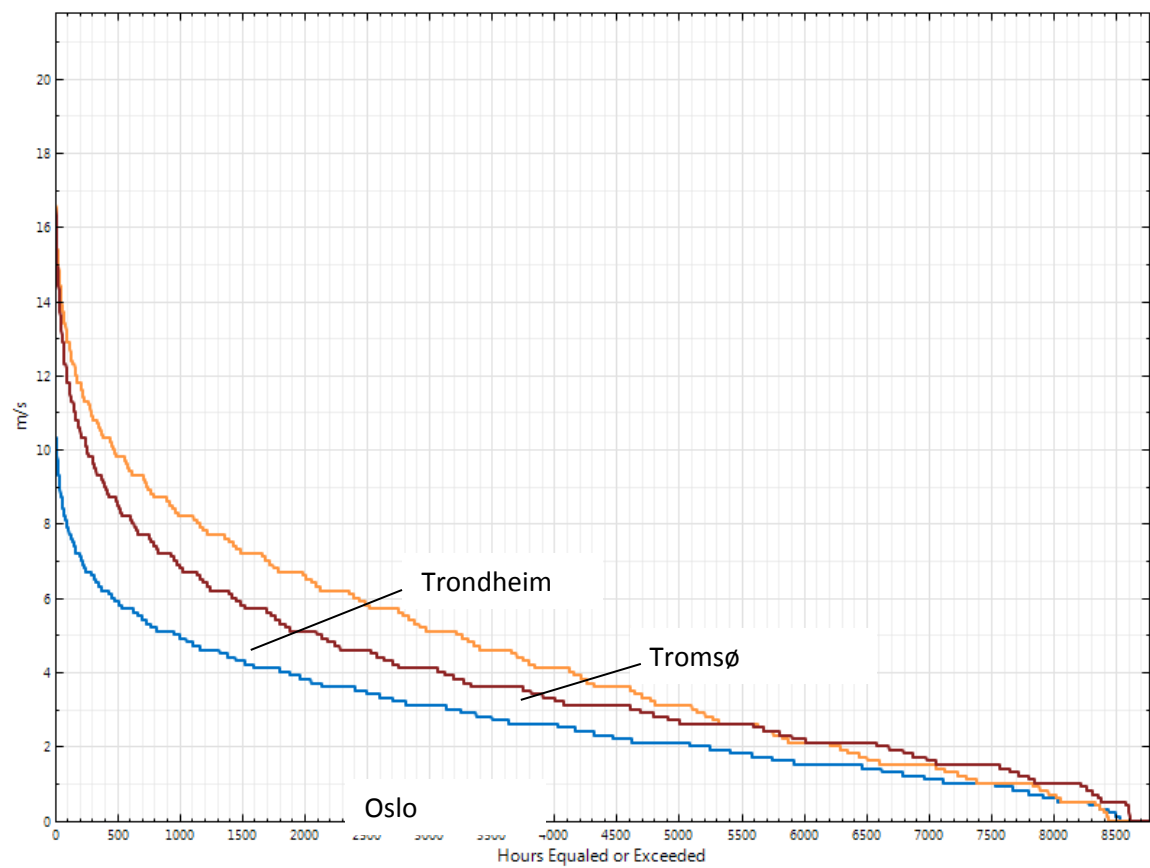


Figure F.3: Duration curve

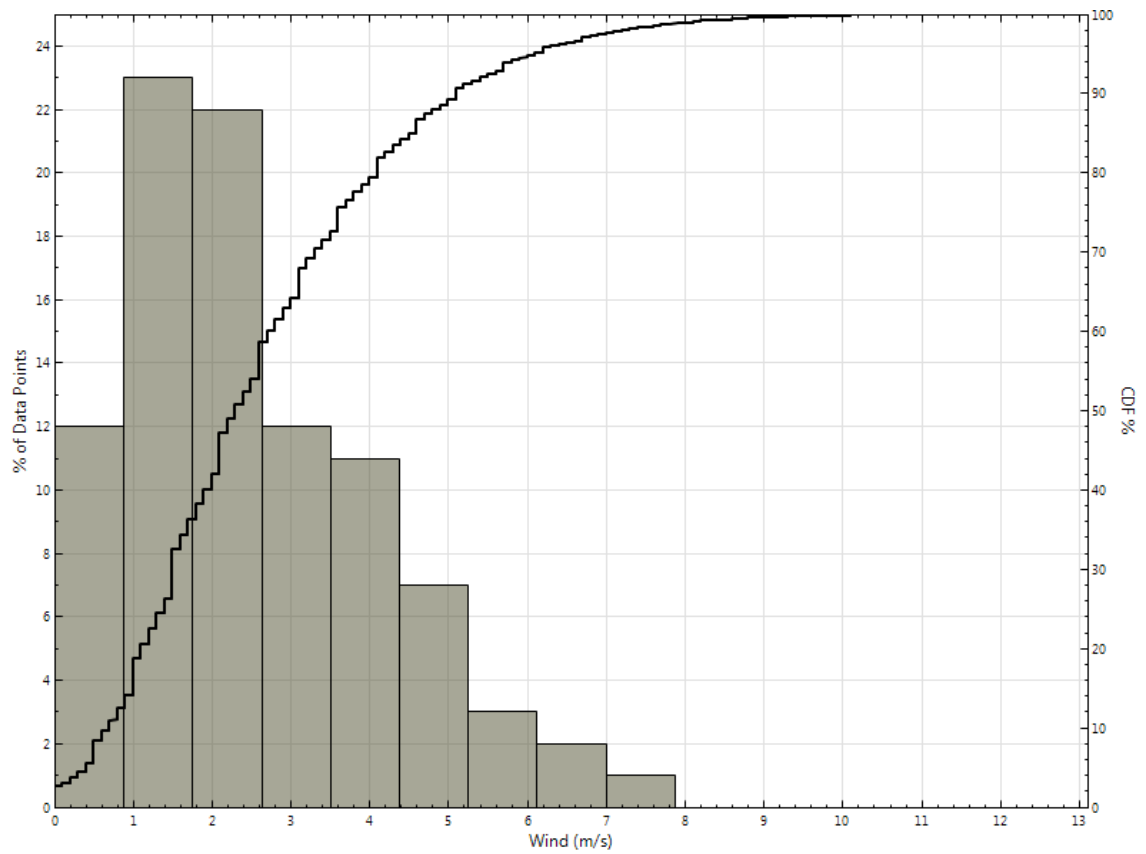


Figure F.4: Oslo

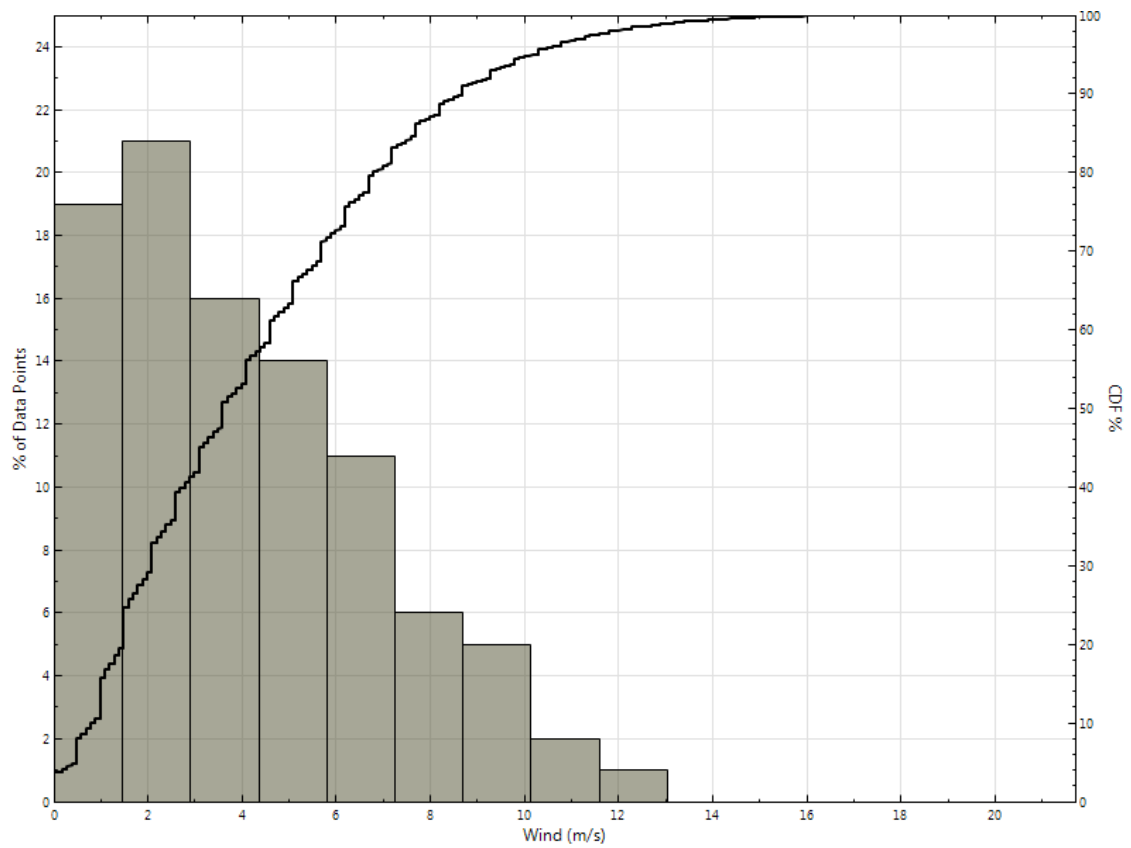


Figure F.5: Tromsø

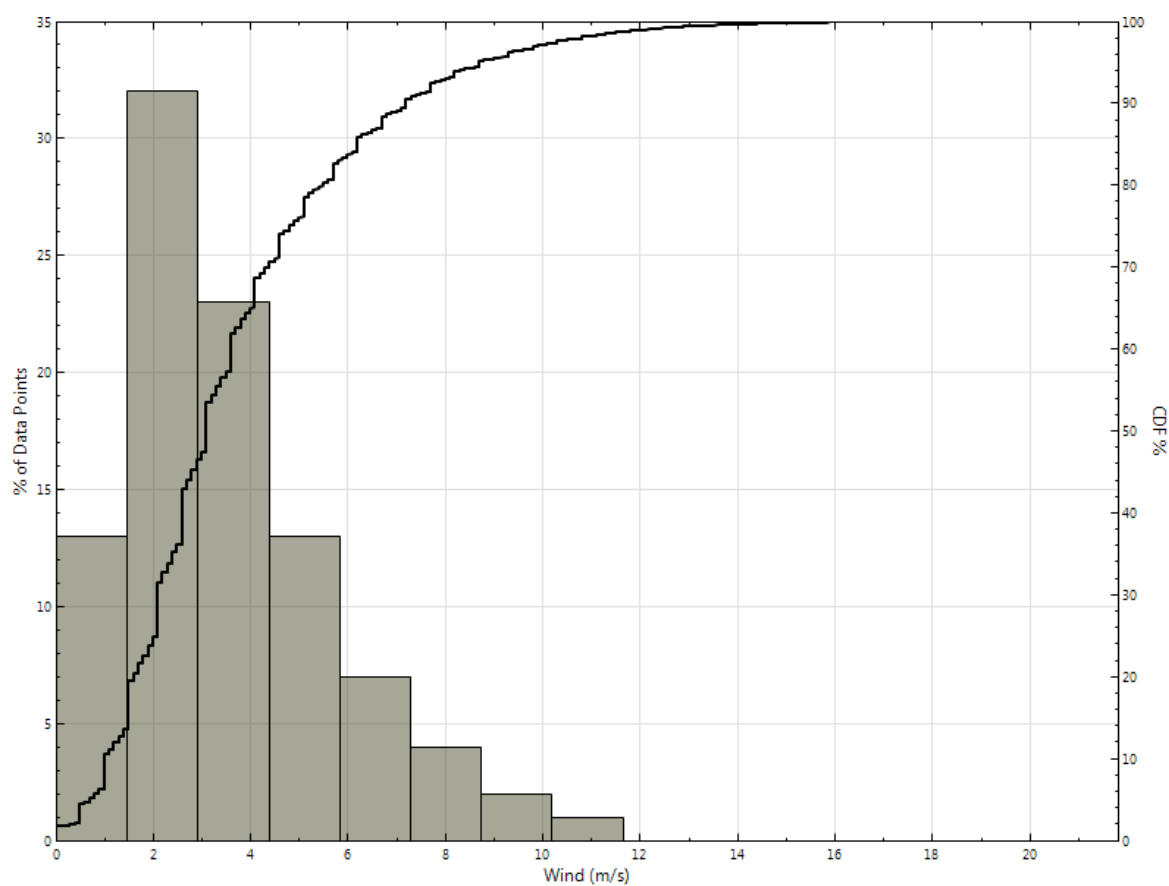


Figure F.7: Trondheim (Værnes)

Table F.1: Roughness factors from NS-EN 1991-1-4

Terrengruhetskategorier		k_T	z_0 (m)	z_{min} (m)
0	Åpent, opprørt hav	0,16	0,003	2
I	Kystnær, opprørt sjø. Åpne vidder og strandsoner uten trær eller busker	0,17	0,01	2
II	Landbruksområde, område med spredte små bygninger eller trær	0,19	0,05	4
III	Sammenhengende småhusbebyggelse, industriområder eller skogsområder	0,22	0,3	8
IV	Byområder der minst 15 % av arealet er dekket med bygninger, og deres gjennomsnittlige høyde overskrider	0,24	1	16
	15 m. Granskogområder			

BUILDING AUGMENTED WIND TURBINES –BAWT

INTEGRATED SOLUTIONS AND TECHNOLOGIES OF SMALL WIND TURBINES

This report analyses barriers and potential for implementing integrated wind turbine technology in Norway. Studies of international projects, measurements, energy simulations, interviews and audits are carried out. The investigations show that location is very important, together with turbine type and size. These results should be taken into consideration when applying new wind turbine technology in urban building design. The project was financed by the Norwegian State Housing Bank (Husbanken).