OULUN AMMATTIKORKEAKOULU

Petri Leppänen

SMALL-SCALE WIND POWER IN THE ARCTIC REGION

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Opinnäytetyö tehtiin tilaustyönä Iin Micropolis Oy:lle osana ”Arctic Energy – Omavarainen pohjoinen” hanketta. Hankeen on rahoittanut Euroopan aluekehitysrahasto Interreg Pohjoinen, Lapin Liitto ja BusinessOulu. Hankkeessa pyritään kehittämään ja testaamaan simulointimenetelmä energiantuotannon mallintamiseen arktisissa olosuhteissa.

Työn tarkoituksena oli tutkia pientuulivoiman soveltuvuutta arktisille alueille ja sen nykytilaa. Työ jakaantui kolmeen pääosaan, jotka ovat teknologia, laitevalmistajat ja talous. Teknologian tutkiminen keskittyi pientuulivoiman eri teknisiin vaihtoehtoihin ja niiden etujen ja haittojen tutkimiseen. Laitevalmistajia haluttiin tutkia, jotta saatiin parempi käsitys pientuulivoiman tilasta. Taloudellinen vertailu keskittyi tutkimaan millaisissa tuulioloissa pientuulivoimala voisi olla taloudellisesti kannattava.

Teknologian ja laitevalmistajien tutkiminen tapahtui pääasiassa internetlähteisiin perehtymällä ja niitä analysoimalla. Taloudelliset laskelmat tehtiin Excel -taulukkolaskentaohjelmalla ja niissä käytettiin lähtötietoina sertifiointiraportteja ja Suomessa vallassa olevia käytäntöjä.

Tutkimusten pohjalta voitiin sanoa, että pientuulivoima on vähitellen kehittymässä varteenotettavaksi energiantuotantomenetelmäksi. Pientuulivoiman tuotantoa löytyi Suomesta ja Ruotsista, mutta isoimmat tekijät tulevat Tanskasta, Isosta-Britanniasta, Amerikasta ja Kiinasta. Näissä maissa pientuulivoimalla on jo selkeä jalansija uusiutuvista energiamarkkinoista. Taloudellisuuslaskelmien perusteella Suomesta, Ruotsista ja Norjasta on löydettävissä alueita, joissa pientuulivoima voi olla kannattava, mutta asennuspaikan valinta osoittautui erittäin tärkeäksi vaiheeksi tuulivoimaprojektissa.

Asiasanat: pientuulivoima, tuulivoima, arktinen alue, kannattavuus,

ABSTRACT

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Thesis was done for Iin Micropolis Oy, as a part of an Arctic Energy project. The project is founded by European development fund Interreg Nord, Regional Council of Lapland, BusinessOulu, Länsstyrelsen Norbotten and Interreg-program in Norway. The project aims to develop and test a simulation method for energy production in Arctic areas.

The aim of the study is to research if small-scale wind power could be applied for Arctic areas. The work is done in three parts, which included technology, manufacturers and economics. Technology study focuses on finding out what choices are available and what are their benefits and weaknesses. Manufacturer chapter concentrates in searching local and other well established products from the market. Economic study is done to understand whether small wind turbines could be profitable in the arctic region.

The thesis was done mainly by researching literature and internet based sources, to get a full understanding of the current state of small wind turbines. Economic calculations were done with Excel. The calculations were done with wind turbine certification based information and Finnish regulations.

Small-scale wind power is gradually becoming a viable option as an energy production method. There are manufacturers in Finland and Sweden, but they are small in comparison to Danish, British, American or Chinese manufacturers. Cost of SWTs has been slowly degreasing and it has made small wind turbines an interesting option for a renewable energy source. According to the calculations small-scale wind power can be profitable in the arctic region, but not everywhere. Annual wind conditions have to be around 5 to 6 m/s, for a profitable installation.

Keywords: small-scale wind turbine, wind power, Arctic region, profitability

TABLE OF CONTENTS

1 INTRODUCTION

This report is a part of a bigger project about Arctic energy. The main objective of Arctic Energy –project is to develop and test a simulation method for self-sufficient and carbon neutral energy production in the Arctic conditions. The project is funded by Interreg Nord, *Regional Council of Lapland, Länsstyrelsen Norbotten and Interreg-program in Norway*. (Arctic Energy.)

This report is about small-scale wind power technology and its economic feasibility. Technology study consists of wind turbine alternatives and comparison between the technologies. The economic analysis chapter includes costs of the technology and its payback time. This report also includes a list of small wind turbine manufacturers.

Wind forms when sun heats the surface of Earth and causes pressure differences. Those differences want to balance out naturally and thus lead to wind. Wind has been harnessed for centuries to power sailboats, grind corn and pump water. Only in the last century has electricity been made from wind energy. (Pimiä - Biktuganov - Gerlitc - Häkkinen – Kakko – Martikainen – Matikkala - Mäkelä – Tuliniemi – Töyrylä 2014, 9.)

The last twenty years have seen very rapid increase in the use of wind power. In the European Union (EU) wind power's share of total power capacity has increased by six-fold since 2000. The total power capacity of wind power in the EU is currently 141 579 MW and its increasing by 12 800 MW annually. Finland had installed little over 1 000 MW of wind power capacity by the end of 2015. Swedish wind power capacity reached 6 000 MW in the year 2015. Norway has the smallest amount of installed wind power capacity in the Nordic with 837 MW. (EWEA 2015, 4.)

2 SMALL WIND POWER

High growth in large industrial wind power has lead the technological development of wind turbines. That has also increased the interest in producing electricity in small-scale. Small-scale wind power is often installed in off-grid locations to provide electricity. Small wind turbines (SWTs) often produce only few kilowatts of energy and are installed as a single-unit. The same basic design parameters apply both to SWT and to large commercial wind turbines. Because power output of wind turbine is relative to wind speed to the third power, the most important thing in planning a wind turbine installation is to find out if your location has enough wind to be able to produce energy. (Abraham 2014, 1.)

Small wind turbines are designed in three different basic models. Most common is the horizontal-axis wind turbine (HAWT). Other models are vertical-axis wind turbines (VAWT), which come with either Darrieus or Savonius -style rotor. Closer inspection of the different models will be presented in the technology chapter. (Abraham 2014, 2.)

2.1 Definition of small-scale wind power

The international energy council (IEC) defines small-scale wind power by swept area. Currently the limit is set to 200 m2 in the IEC standard for small wind turbines. (IEC 61400-2:2013 2013.) Swept area of 200 m^2 refers to about 50 kilowatts of power depending on wind turbines efficiency and rated wind speed. In many countries a limit of 100 kW is acceptable to be connect directly to low voltage grid. (EWEA 2009a, 125.) In Finland maximum total electricity output of 2MVA is considered small-scale production and anything bigger than that is commercial production. (Eklund Esa, 2011.) The trend is to move the definition of small wind power to 100 kW. This is driven by North American and European markets. It would be beneficial to agree on a set standard of power output, so that comparison of markets would be comparable. (WWEA 2016a, 11.)

2.2 Market of small-scale wind turbines

According to latest reports world capacity of small wind turbines was 830 332 kW with 944 848 units registered. World Wind Energy Agency (WWEA) estimates that there are more than one million units installed due to the fact that not all turbines are registered. The growth has been relatively steady for last five years as seen in figure 1. (WWEA 2016a, 3.)

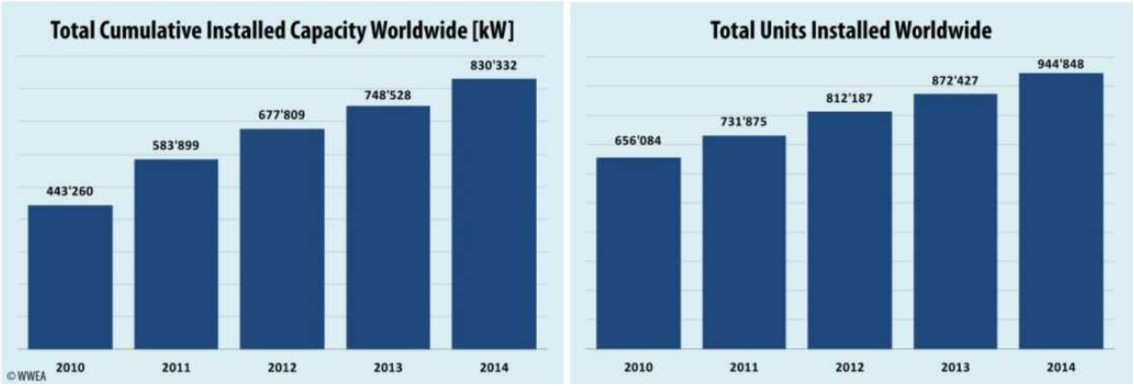


FIGURE 1 Worldwide capacity and number of units installed (WWEA 2016a, 3.)

Chinese market is by far the biggest of all with the 72 % share of installed units. United States of America comes second with 19 % of installed units. That leaves only 9 % to the rest of the world, but when you compare total installed capacities, the situation looks a lot different. Then China has only 41 %, USA 30% and rest 29% as can be seen from figure 2. (WWEA 2016a, 5.)

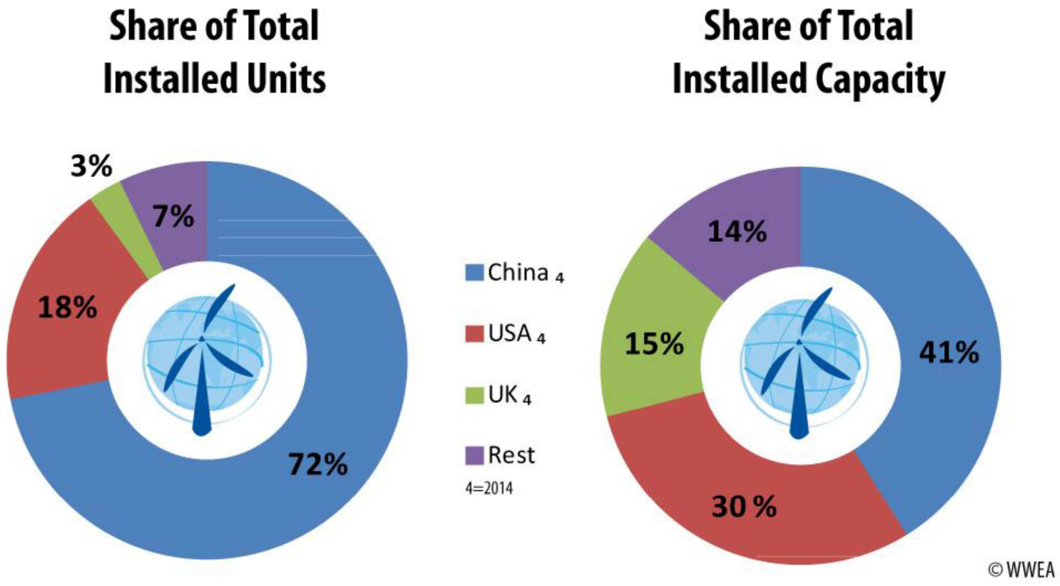


FIGURE 2 Comparison of installed units to installed capacity by country (WWEA 2016a, 6.)

In China average size of SWTs is a lot smaller than in the rest of the world. Especially European market seems to have recently been toward larger turbines. For example United Kingdom and Italy have seen big increase in 20-100 kW SWTs due to Feed-in tariff schemes. (WWEA 2016a, 6.)

Manufacturing of small wind turbines is mainly done by Canada, China, Germany, UK and USA. There are a total of 330 SWT manufacturers and over 300 subcontractors in the world. China is the biggest manufacturer of SWTs with capacity of approximately 180 000 units per year. (WWEA 2016a, 7.)

Small wind turbine market is predicted to increase in the coming years. WWEA predicts at least 11 % growth in installed capacity. According predictions annual installed capacity could increase to 240 MW by 2020. Figure 3 shows WWEA’s predictions of SWT capacity. (WWEA 2016a, 10.)

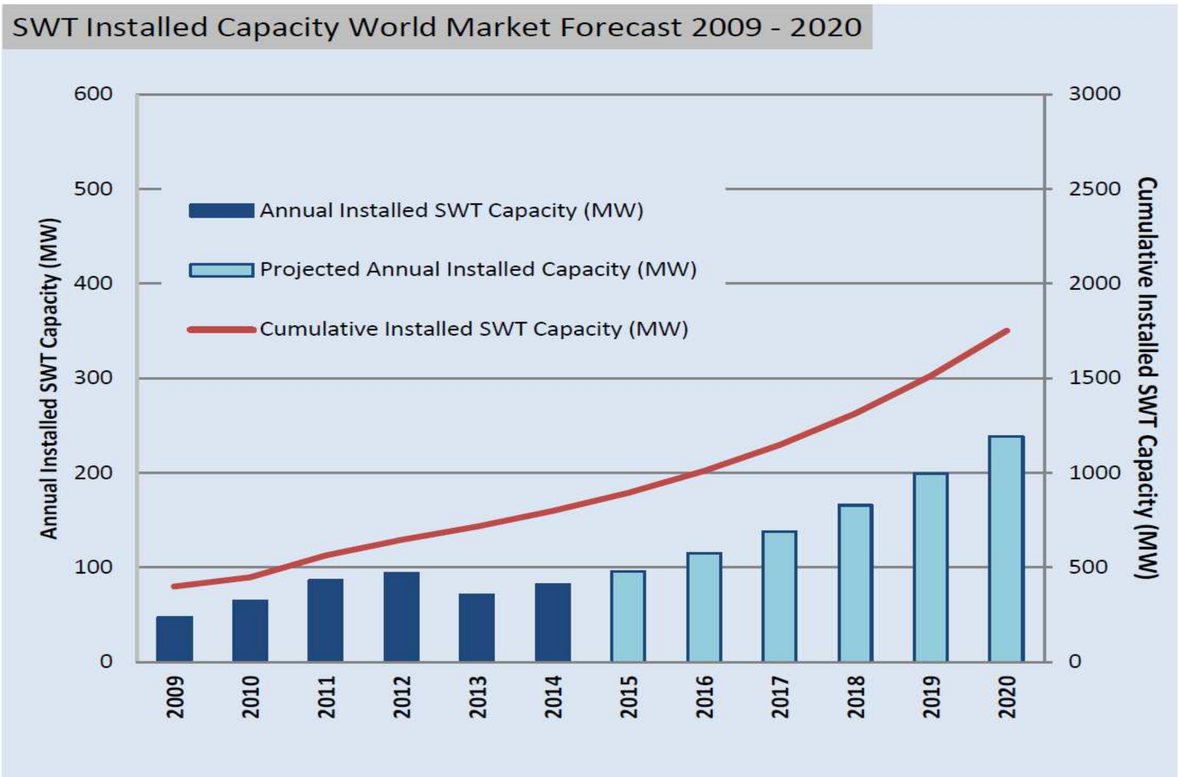


FIGURE 3 Forecast of Small Wind turbine capacity (WWEA 2016a, 10.)

2.3 Cost of small wind turbines

Small wind turbine installation cost consist of more than just the price of turbine. It can contain also the mast, cables, power electronics, foundation, auxiliary devices, delivery and installation. That causes big variations in the price between countries and even projects. (WWEA 2016a, 8.)

U.S. Department of Energy has published, in the 2014 Distributed Wind Market Report, installation costs of small wind turbines in three categories:

- 2,5 kW: 7200€/kW
- 2,5-10 kW: 6300 €/kW
- 11-100 kW: 5300 €/kW

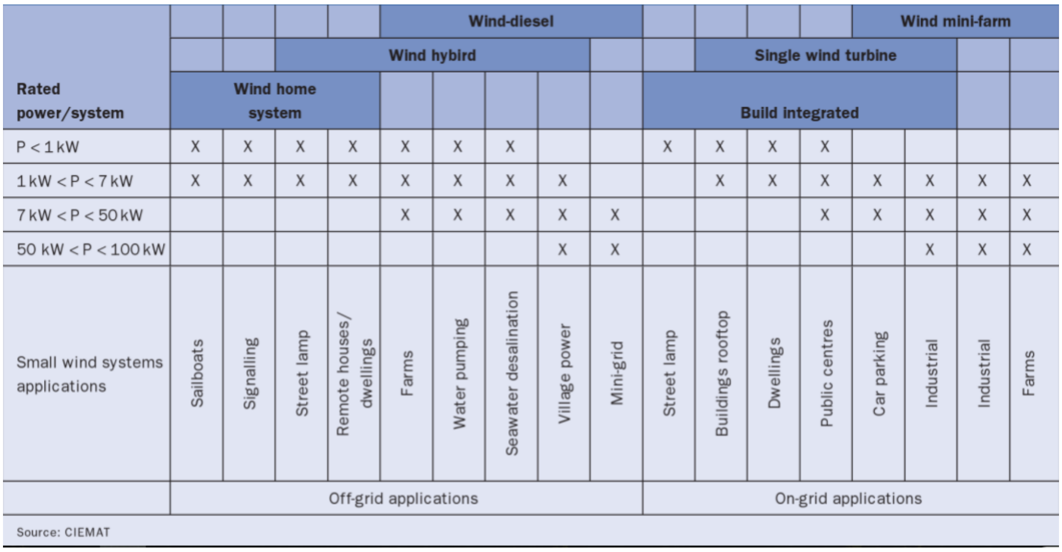
RenewableUK has released prices in 2014 for two categories of small wind turbines in the UK market:

- 1,5-15 kW: 5400 €/kW
- 15-100 kW: 4300 €/kW

Chinese industry has presented in 2011 an overall price for small wind turbines of 1500 €/kW, which is noticeable cheaper than the other markets. These prices can only be used as a guideline and not in economic analysis, due to the fact that installation cost is a sum of many parts that vary in every project. (WWEA 2016a, 8.)

2.4 How small wind turbines are used?

Small wind turbines can be connected on- or off-grid. On-grid means that turbine is connected to electricity grid and can transfer excess production to other users. Off-grid installations on the other hand require batteries and some sort of dumb load to get rid of over production. Figure 4 describes where the two applications are most commonly used. Most often on-grid installations have bigger power output, but there are over 50 kW systems powering isolated villages. (EWEA 2009a, 126.)



Rated power/system					Wind-diesel									Wind mini-farm			
			Wind hybird								Single wind turbine						
	Wind home system									Build integrated							
P < 1 kW	X	X	X	X	X	X	X			X	X	X	X				
1 kW < P < 7 kW	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X
7 kW < P < 50 kW					X	X	X	X	X				X	X	X	X	X
50 kW < P < 100 kW								X	X						X	X	X
Small wind systems applications	Sailboats	Signalling	Street lamp	Remote houses/ dwellings	Farms	Water pumping	Seawater desalination	Village power	Mini-grid	Street lamp	Buildings rooftop	Dwellings	Public centres	Car parking	Industrial	Industrial	Farms
	Off-grid applications									On-grid applications							
Source: CIEMAT																	

FIGURE 4 Applications of small wind turbines (EWEA 2009a, 126.)

2.4.1 Off-grid

Most often SWTs are installed to off-grid locations, where they provide electricity to single residences. Off-grid systems can be categorized to three different sections. Wind home is the smallest of them with only few kilowatts of power. These systems often produce direct current (DC) for batteries, where it is used for lighting and small electronic appliances. (EWEA 2009a, 127.)

Hybrid systems are little bit larger installations, where some other source of energy generates part of the electricity. In many cases wind power is combined with photovoltaic solar panels. Hybrid systems have often also a diesel-generator installed as a backup. These systems run mainly on DC power and have batteries for storage, only in recent years have alternating current (AC) systems been introduced to market. Hybrid systems are a good choice for off-grid, because they provide better reliability and flexibility for production. A simple diagram of a hybrid system can be found in figure 5. (EWEA 2009a, 127.)

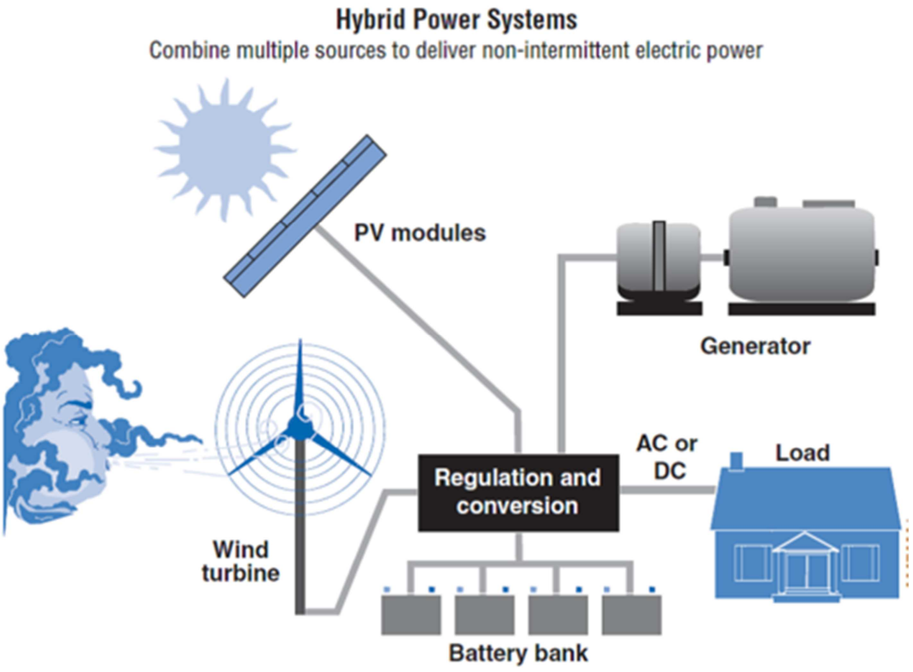


FIGURE 5 Off-grid hybrid system. (OpenEI.)

Largest off-grid systems are wind-diesels. In these systems diesel generator play major role in producing electricity and not just backup. Most often in wind-diesels the SWT have been added to existing diesel system and that is why they usually have only short-term storage for electricity. (EWEA 2009a, 127-128.)

2.4.2 On-grid

Grid connected applications have seen bigger growth in the last decade than off-grid. This is mainly due to North American and European markets. Where government subsidies have made investments more viable. On-grid SWTs have usually lager power output than off-grid. On-grid systems are more likely to be installed in urban environment, because they require electric network. Grid connection provides some benefits to the user, for example it does not require storage, and excess electricity can be fed to the grid and even in some cases sold to other users. Electricity grid provides backup energy to the user, when wind production does not meet the demand. This makes the planning of the SWT a lot easier. On-grid systems require inverters that transfer wind turbines DC power to the grid specific AC voltage and frequency. figure 6 illustrates an installation of on-grid system. (EWEA 2009a, 128-129.)

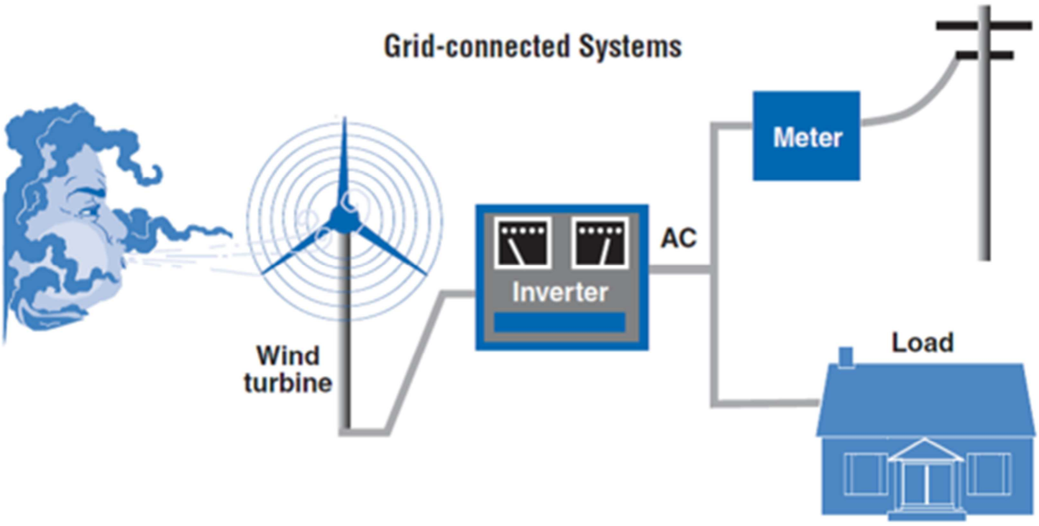


FIGURE 6 On-grid system. (OpenEI.)

2.5 Installation location

Most important factor when choosing an installation location for a small wind turbine is wind conditions. The simplest way to figure out wind conditions is to search for local Wind Atlas data. In Finland wind conditions can be found from Finnish Wind Atlas website. They provide forecasted wind speed and wind roses from 50 to 400 meters. 50 meters is a bit high for SWTs, so for more detailed information mathematical calculations are required. Figure 7 is an example of Finnish wind map. (Suomen tuuli atlas.)

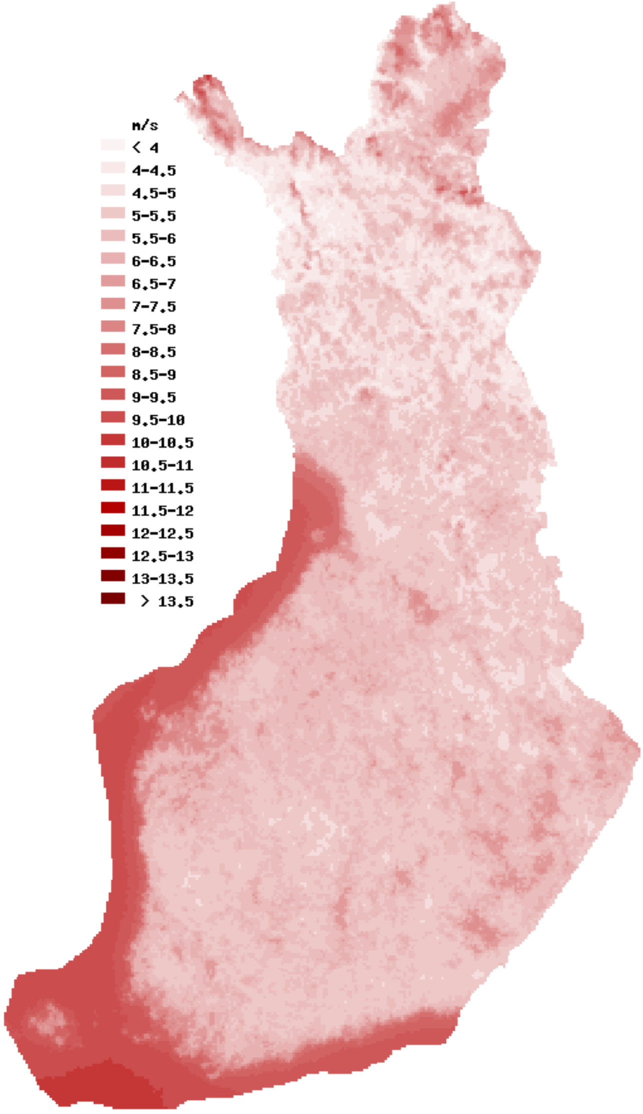


FIGURE 7 Finnish wind conditions in February at 50 m height (Suomen tuuli atlas.)

Swedish and Norwegian wind data can be found from windmap.se. It is a website combining Norway's Kjeller Vindteknikk's and Sweden's Weathertech's wind resource maps. Norway's data is from 50-120 m and Sweden's 48-140 m. (Windmap, links About.)

Wind roses are illustrations of wind speed and direction. They provide information for understanding where to install your turbine. It makes sense to place turbine in a location where wind conditions are optimal. Figure 8 shows an example of a wind rose. (Suomen tuuli atlas, links Tuuliatlaksen käyttöohje.)

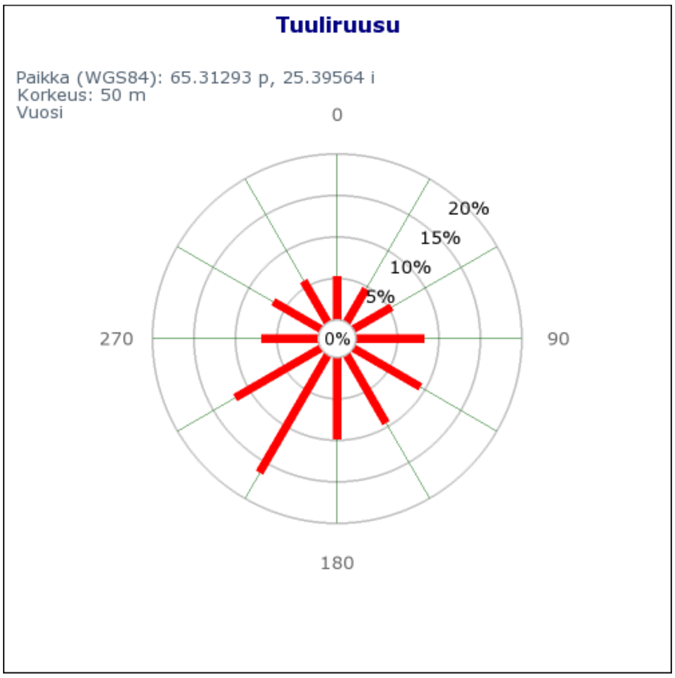


FIGURE 8 Wind rose model (Suomen tuuli atlas, links Tuuliatlas-karttaliittymä -> taso 2500 m -> tuulennopeus.)

Commercial scale Wind Power do not just rely on wind atlas data, they measure accurate data from the installation location. One or more meteorological masts are placed on the site and wind data is gathered for at least a year to provide accurate seasonal information. Mast should reach the turbine hub height, so that measurements are comparable to avoid uncertainties. Masts are equipped with anemometers that are installed at different heights. In cold climates also temperature sensors are vital to provide icing information. Figure 9 is an example of an anemometer on top of a meteorological tower. Measuring wind speed is not cheap and takes a lot time, so it is not common practice in SWT projects. (EWEA 2009a, 38-41.)

FIGURE 9 Anemometer at the top of the meteorological tower (Luxembourg Beidweiler anemometer.)

Second most important thing is to provide undisturbed wind to your turbine. As seen in figure 10, wind turbine should be placed at least twice as high as tallest obstruction to be clear of turbulent air flow. Other possibility is to move the turbine to an open field, where obstructions are far. Turbulent air flow causes rapid changes in wind speed and direction. That leads to losses in power production. If installation location is poor, it can disturb power production. Best option would be to place turbine on top of a hill without any obstructions to wind, because average wind speed increases the higher you go. A cheap and simple way to figure out if your site has turbulent air flow is to fly a kite with streamers tied to the kite string. Observing how the streamers flutter in the wind can recover conditions in your installation location. (Gipe 2004, 270; OpenEI.)

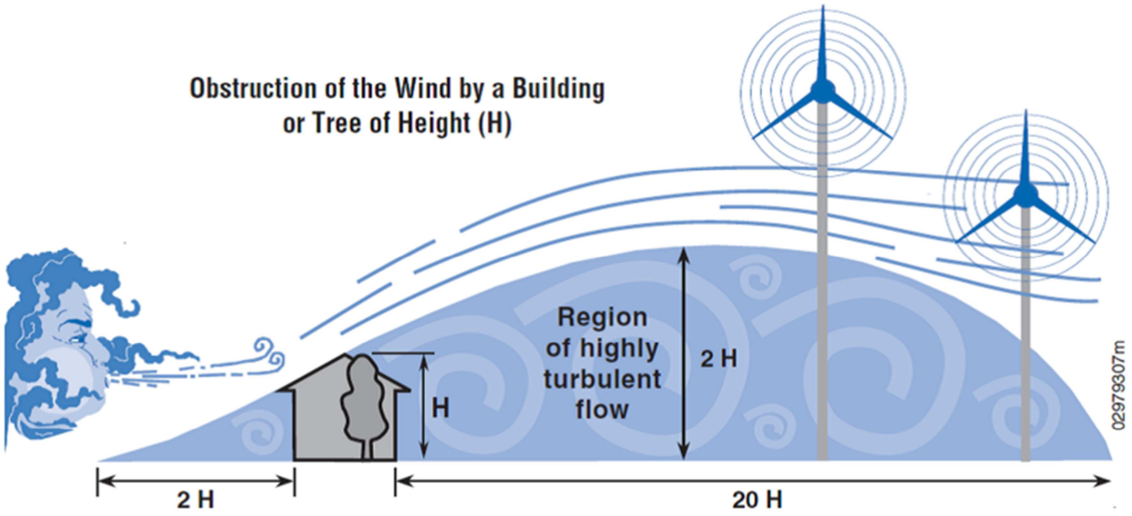


FIGURE 10 How houses and trees obstruct wind (OpenEI.)

2.6 Legal requirements for small wind turbines

Every country has its own laws and regulations when it comes to wind power. Small wind turbines have often a pit simpler restrictions, than large-scale wind power. Often building permits are sufficient for SWTs, but some countries may require planning permission, environmental impact assessment and other more complex documentation. (Gipe 2004, 272-274.)

2.6.1 Finland

In Finland SWTs require building- or action-permit depending on the height. There is not any set limitations to height, but the limits are set by municipalities and vary a lot. Requirements also take in consideration of visual appearance and noise levels. That is why it makes sense to contact local authorities to figure out what your project requires. (Ympäristöministeriö 2012, 29.) Over 30 MW or 10 wind turbine projects require automatically Environmental Impact Assessment (EIA). Smaller projects may require EIA if they locate near environmentally sensitive nature. For example rare plant life, preserved animal spices or areas listed in Natura 2000. (Pimiä et al. 2014, 62-63)

2.6.2 Sweden

Sweden’s restrictions are based on height and the number of wind turbines. A group of two or more turbines higher than 150 meters and group of seven or more turbines higher than 120 meters, require environment permit. Over 50 meter WTs and groups of two or more need to be reported to the local authorities. Sweden does not require building permit for under 20 meter WTs unless the wind turbine is placed on a building or when the distance between the site boundary and the wind turbine is shorter than the wind turbines height. Local municipal has permission to decide what plans and permits is needed, so it is crucial to contact them. (Nilsson 2010.)

2.6.3 Norway

In Norway municipalities can give permissions to small wind turbines under 1kV according to Norwegian Planning and Building Act. Wind Turbines larger than 1 kV need license from Norwegian Water Resources and Energy Directorate. Applicants must follow Energy Act, Planning and Building Act and a number of other laws and regulations in the licensing process. In Norway Environmental Impact Assessment is required if the Wind project exceeds capacity of 10 MW or initial screening indicates significant risks to environment. In addition to licenses all Wind Turbines must follow local municipals land use plans. (Vindkraftens ABC 2013, 48-51.)

2.7 The acceptance of wind power

Wind energy generally has a positive acceptance, because of it being clean and renewable energy. In surveys conducted in European Union 71% were generally in favour of wind energy. Due to the fact that wind turbines are fairly visible and close to accommodation, they tend to have some opposition. Social acceptance is fairly complex and multidimensional subject. It contains visual appearance, landscaping, noise emission, ecologies, knowledge, attitudes, ownership and politics to name a few. Community acceptance is often reached with open dialog to citizens and by engaging them to the project. (EWEA 2009a, 399-410.)

In a survey conducted in the United Kingdom SWT acceptance was mainly positive. Under a fourth of the people found SWTs unacceptable and almost the same number were against having them in proximity of their homes. This is a good example of “not in my back yard” mentality, where things are acceptable when they do not affect personally. The positioning of SWT was found to be important in gaining acceptance. Fields were generally better locations than others. Planning guidance might enhance acceptance, by setting rules for size, installation and noise of SWTs. Citizens perceptions should be taken into consideration when informing them. (Hanley– Minderman - Park - Paton– Robertson– Tatchley 2016.)

2.8 Concept of community wind

Community wind is based on local people investing in a local wind turbine project and being able to have influence on it. Community wind is a part of bigger concept of community power, which aims to promote distributed renewable energy. Often citizens own over 50 % of the company that is established. They will not just receive electricity from the company, but also share the profits. Community wind business models range between energy cooperatives, joint investments, local investments and closed-end funds. World Wind Energy Agency (WWEA) is currently developing community wind to be able to spread it around the world. WWEA has developed the three main elements of community wind: (WWEA 2016b, 3-4.)

1. Locals own at least majority of shares
2. Community has majority of the voting rights
3. Most of the social and economic benefits are returned to the community

Community wind has helped the implementation of wind power in Germany, because local investors are more interested in investing to projects that impact their life even though return might be low. In many cases community wind has helped the acceptance of wind projects. (WWEA 2016b, 5.)

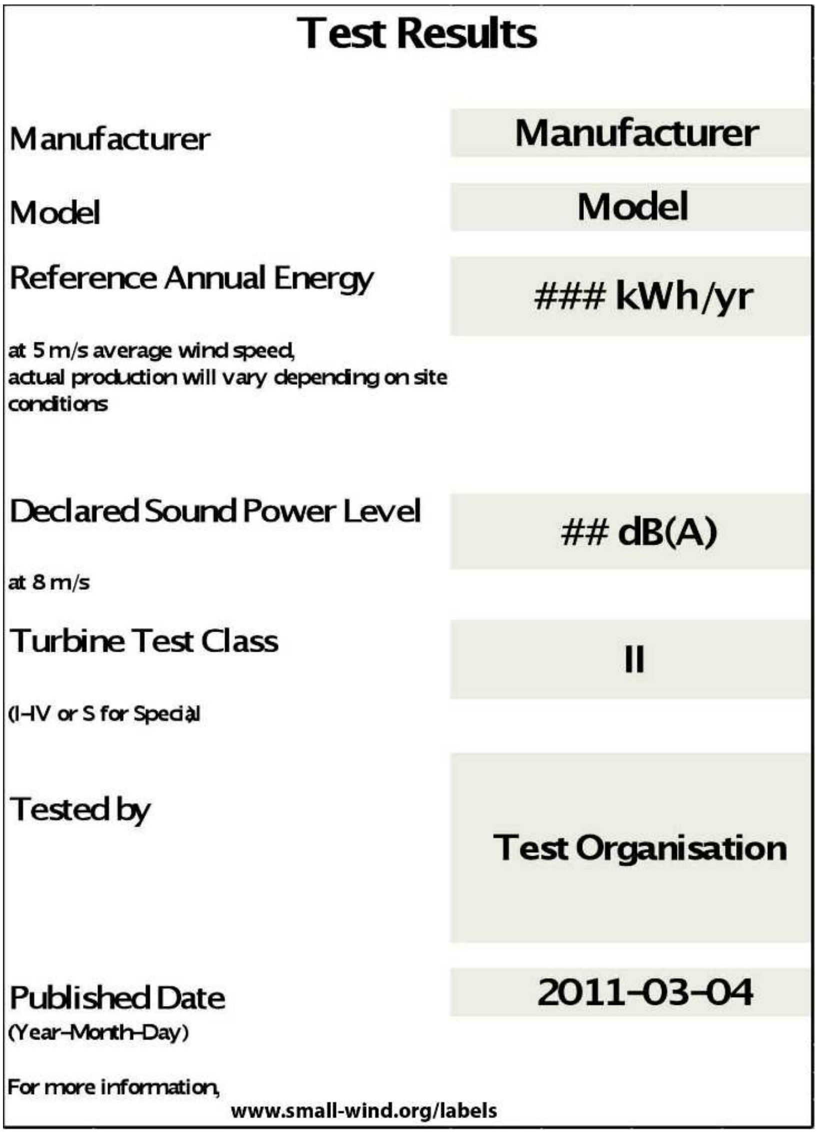
2.9 Future development of small wind turbines

Manufacturers of small wind turbines still have a lot to do to make their products economically worthy solution. At the moment off-grid products are relatively economical, but on-grid solutions have so much competition that they still have way to go. Blade and rotor design is an ongoing development part of SWTs. Currently blade design is aiming on improving performance and reducing noise emission, with new aerofoil design. Also new blade materials, such as thermoplastics, are an interest for manufacturers. Pitch systems are also in development, because current furling systems cause high noise and vibrations. For off-grid systems better storage solutions are the key development area. On-grid systems on the other hand needs better power electronics. (EWEA 2009a, 136-137.)

Current IEC standards need future development to implement them better in use. They are well accepted by professionals of the trade, but much used in practice. Manufacturers tend to think that using IEC standards is difficult and costly. Most improvement is need in standardisation for testing of SWTs. Currently there is no standard for testing on-grid SWT products. Also noise emission tests need to be development. (EWEA 2009a, 137-138.)

2.9.1 Labelling

International Energy Agency has developed consumer labels for SWTs. Idea is that all turbines that have been tested and approved by IEC standards would be able use it. Label would contain useful information to consumer about the product. All Information would be in according with the standards and therefore make comparing products a lot easier. Figure 11 is a model of the consumer label. (Small wind, links Quality -> Consumer label.)



Test Results

Manufacturer	Manufacturer
Model	Model
Reference Annual Energy at 5 m/s average wind speed, actual production will vary depending on site conditions	### kWh/yr
Declared Sound Power Level at 8 m/s	## dB(A)
Turbine Test Class (I-IV or S for Special)	II
Tested by	Test Organisation
Published Date (Year-Month-Day)	2011-03-04

For more information, www.small-wind.org/labels

FIGURE 11 Model of consumer label (Small wind, links Quality -> Consumer label.)

2.9.2 Urban design

New trend in small wind turbines is making products integrate into urban environment better. One of the most interesting is NewWind's Aeroleaf design which tries to disguise turbines in to a tree shape. The product contains several vertical-axis wind turbines as "leafs" and a mast that is shaped like a tree. A single tree has capacity of 4.1 kW and is about 10 meters tall. An example of an installed product in figure 12. (Newwind, links Innovations.)

FIGURE 12 A tree shaped wind turbine by NewWind (Newwind, links Innovations.)

2.9.3 Invelox wind turbine

Sheerwind has developed a new type of wind turbine concept, where wind is gathered at the top of a tower and funnelled true a venturi tube that has normal wind turbine. The venturi effect increases the wind speed and so in theory Invelox could produce more electricity at low wind speeds. Figure 13 describes in detail how the Invelox system works. The inlet can be netted to prevent animals from entering the machine. Some studies indicate that placing two or three turbines in series inside the tube can increase production. According to manufacturer this technology could be scaled from micro-generation to large-scale production. Sheerwind has estimated that Invelox would cost 1000-20000 dollars per kilowatt depending on size. (Sheerwind, links Technology –> How it works.)

FIGURE 13 Invelox wind delivery system. (Sheerwind, links Technology –> How it works.)

3 SMALL WIND TURBINE TECHNOLOGY

There are three basic types of small wind turbines, but they all have the same principal of turning winds kinetic energy into mechanical energy. Horizontal-axis wind turbines (HAWT) are the more common type, with often three blades that spin at the top of the tower. Vertical-axis wind turbines (VAWT) are divided into two separate models called Darrieus and Savonius. Both of them turn around a vertical-axis, which is why they are called vertical-axis turbines. (Abraham 2014, 2.)

3.1 Vertical axis turbines

All vertical axis wind turbines are based on the concept that wind turns the turbine around a vertical axis. The difference between the two VAWT models is how they capture the wind. Darrieus works with lift and Savonius relays in drag forces to rotate. (Abraham 2014, 2.)

3.1.1 Darrieus-type wind turbine

Darrieus style VAWT was invented by a French engineer George Jeans Mary Darrieus in 1931. Darrieus-type VAWTs are based on blades that are installed vertically. The blades can be straight or curved, but they operate similarly. The blades are connected to a vertical-shaft and they turn it by lift forces. Different types of Darrieus VAWT are illustrated in figure 14. (Abraham 2014, 45-46.)

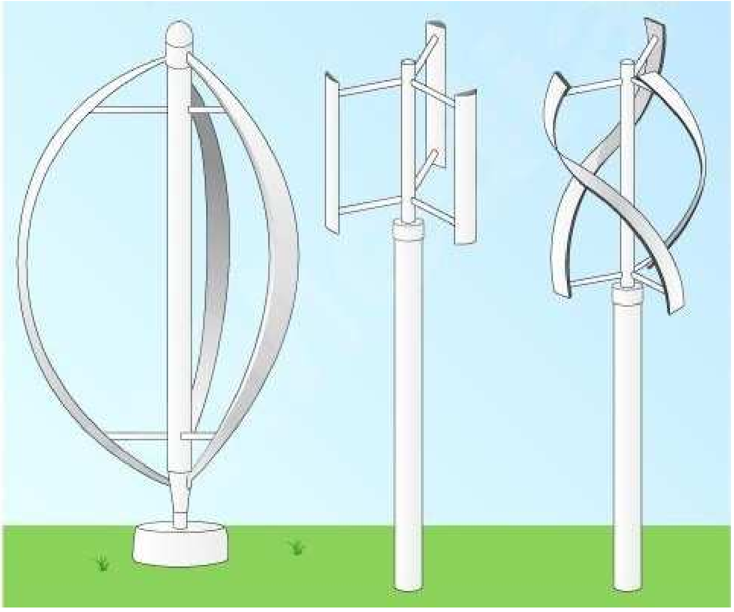


FIGURE 14 Different Darrieus-type wind turbine models (Eolienne flexible.)

The biggest advantages of Darrieus-style VAWTs are that the generator can be placed on the ground and the turbine can capture wind from any direction without a yaw system. On the other hand they suffer from self-starting problems and vibration damage to support structure. There are at least 11 variations of the Darrieus VAWT and they all have different attributes that improve on the basic design. For example bending of the blades increases its structural strength, but is more complex to build. (Abraham 2014, 46-48.)

Darrieus-type VAWTs can operate at low wind speeds when they are running, but they suffer from start-up problems. The so-called self-starting problem has been widely studied and several design-optimizations have been presented. For example variable pitch systems for straight blade VAWTs and new cambered aerofoil design have helped self-starting. Figure 15 represents how hard it is to capture wind with basic straight blade Darrieus-style wind turbine. (Abraham 2014, 48-52.)

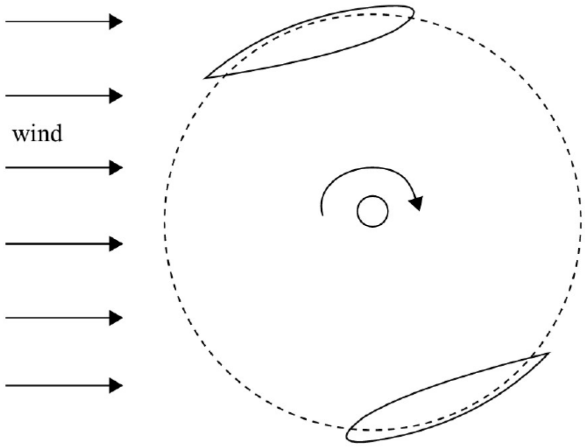


FIGURE 15 Air flow diagram for Darrieus-type VAWT (Abraham 2014, 74.)

VAWT design gives it some benefits over HAWTs. The possibility to receive wind from any direction also known as omni-directionality, helps production in turbulent and chancing wind conditions. This makes possible to install VAWTs in places where HAWTs do not operate efficiently. VAWTs are often used in urban areas for that reason. Also low noise emissions help VAWTs implementation to urban areas. Generators location at the bottom allows it to be big and bulky, and therefore made more reliable, efficient and cheaper. It also makes the requirements for foundations a lot smaller than with HAWTs. (Bernhoff – Eriksson – Leijon 2006.)

Darrieus-style Wind Turbines almost vanished in the late 1990's. They suffered from poor reliability and performance. In some cases blades broke catastrophically, due to fatigue. New interest has risen in past years to develop this style of turbines, because of its simplicity, omni-directionality and low noise emissions. Modern materials and new designs may help to improve the sustainability of products. (Gipe 2013a.)

3.1.2 Savonius-type wind turbine

Basic difference between Darrieus- and Savonius-style wind turbines is the way they are driven. Darrieus turns by lift-force and Savonius by fluid drag forces. Savonius turbine was invented by a Finnish engineer Sigurd Johannes Savonius in 1922. Savonius turbine in its simplest form is a cylinder cut in half and joined to gather in an “s”-shape as shown in figure 16. Wind blows in to the concave side of the turbine and turns the turbine on its axis. A model of the operation of Savonius-type wind turbine can be seen on figure 17. (Abraham 2014, 65-66.)

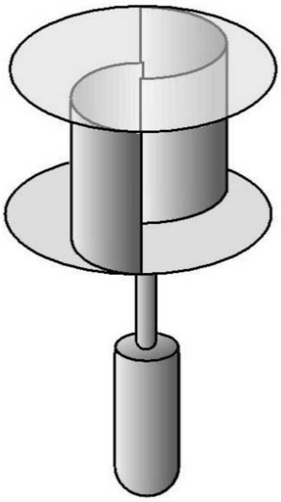


FIGURE 16 Diagram of a Savonius wind turbine (Excluss MagLev.)

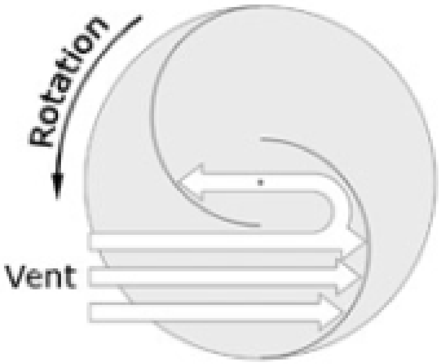


FIGURE 17 Air flow diagram of a Savonius turbine (Excluss MagLev.)

Due to the design of the turbine it has low rotational speed, which causes less vibrations. This helps the turbine to operate at low wind speeds. Some models have even under 3 m/s cut-in speed. Savonius turbines are omni-directional and therefore operate well in changing wind directions. The simple design has its benefits: it reduces price and simplifies assembly. On the other had Savonius wind turbines suffer from low coefficient of power, which often makes it economically unviable. (Abraham 2014, 66-67.)

Savonius-type wind turbine has high torque and is that why often used in water pumping. Some models are also used for ventilation. In electricity production Savonius-type VAWTs are used for small-scale off-grid locations. The simple and reliable nature of the model combined with a battery system provide adequate power for lighting and small electric appliances. New application for this type of VAWT is providing electricity for cellular communication towers. In these situations the turbine would be a part of a hybrid system. Savonius wind turbines have been combined with Darrieus wind turbines to overcome each other's problems. Savonius increases operation at low wind speeds and helps self-starting. Darrieus-type blades increase efficiency at higher wind speeds. Figure 18 illustrates how combined turbines are build. (Abraham 2014, 67-68.)

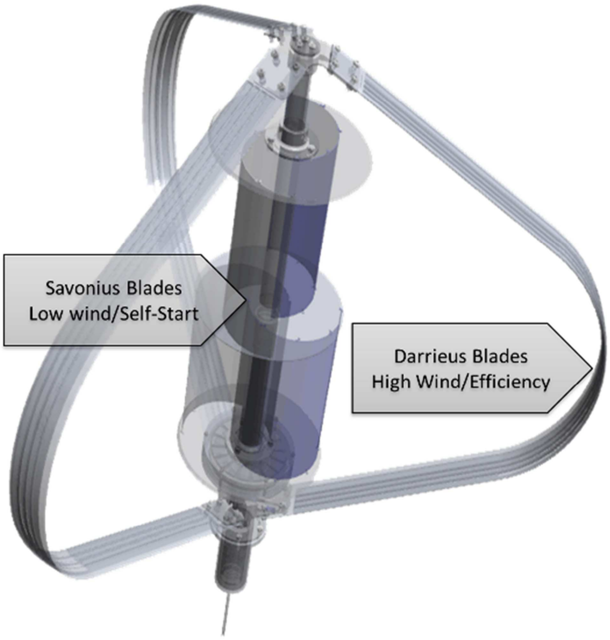


FIGURE 18 Combined Savonius and Darrieus wind turbine. (Excluss MagLev.)

Even though Savonius-style wind turbines tend to self-start easily, some wind angles produce problems. When wind starts to blow at a direction where it hits mainly the convex part of the turbine blades, self-starting can be a problem. To avoid this problem, manufacturers have started to multi-stag Savonius turbines. When two turbines is staged, they are placed in 90° angle of each other, to maximize wind capture. In figure 18 two Savonius-type turbines have been staged on top of each other. Multi-staging settles the torque curve, without any significant loss to peak torque. (Abraham 2014, 77-78.)

Savonius-style wind turbines are often installed in locations where wind conditions are challenging. By modifying the basic design of the Savonius turbine even 30 % coefficient of power can be reached. This makes Savonius turbines noteworthy option in small-scale off-grid locations. Future design is set to reduce weight and price of products, to make them more viable. (Abraham 2014, 87.)

3.2 Horizontal-axis wind turbines

The most common modern wind turbine is the Horizontal-axis wind turbine. These turbines are visually based on the traditional windmills, where blades turn around a horizontal-axis. Even though visually similar the old windmills are driven by drag and the modern turbines are lift-driven. This makes the modern turbine a lot more efficient. Modern HAWTs are more powerful, but produce less torque than the traditional windmills. Old windmills were used to grind grain and pump water. HAWTs are today used mainly in electricity production and there efficiency and power is more important than torque. In figure 19 a modern HAWT windfarm is placed close to an old Windmill. (Abraham 2014, 93-94.)

FIGURE 19 Traditional windmill in front of a windfarm in Netherlands (Goliath mill.)

Last few decades have seen big rise in commercial wind power and the chosen technology has been HAWT. Today large-scale HAWTs produce 1-5 MW of power and are up to 150 meters tall. Small-scale HAWT production is following the steps of large-scale production and gaining popularity. People see small-scale more acceptable for applications where turbines are placed closed to civilization. Small-scale HAWTs have still some catching up to do before they reach cost-effectiveness and performance of large-scale turbines. HAWTs can be considered small-scale when their power output is up to 100 kW, which means approximately rotor diameter of 19 meters. (Abraham 2014, 94-95.)

Main components of HAWT is rotor, nacelle and tower. The rotor consists of blades and the hub. Size of the rotor dictates the whole rest of the system, because rotors swept area is relative to power. Rotors aim is to catch and convert winds kinetic energy in to mechanical energy. Inside the nacelle is the driveshaft, braking system and the generator. Tower supports and raises nacelle and rotor into the operation position. Figure 20 illustrates a simple small-scale HAWT diagram. (Abraham 2014, 95-96.)

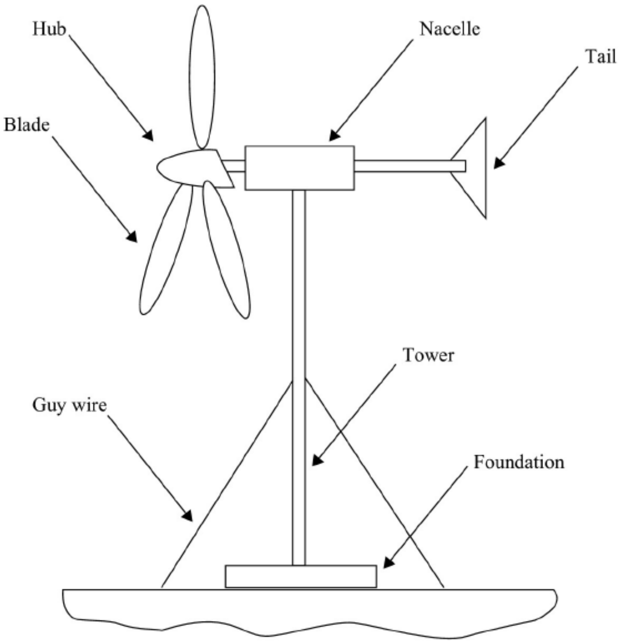


FIGURE 20 Small-scale wind turbine diagram. (Abraham 2014, 96.)

3.2.1 The Rotor

Hubs role in the rotor assembly is to support blades and connect rotor to driveshaft. Rotor can be built to work up- or downwind as seen on figure 21. Upwind is the more common style where rotor is turned towards the prevailing wind. With the downwind style the rotor is downwind of the tower. Downwind systems have slightly downwind swept blades that help turn the turbine to the wind. Downwind rotors are not popular, because the tower blocks part of the swept area and turning does not work reliably with low winds. (Gipe 2004, 90-93.)

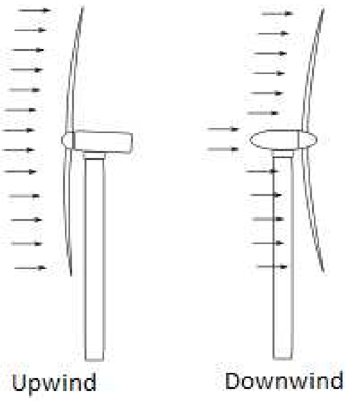


FIGURE 21Comparison of upwind and downwind HAWT. (Yaw system.)

HAWT can operate with a single blade, but it then requires faster angular velocity to catch enough wind. Single blade design is also less effective and emits more noise than two or three bladed models. Single blade models need a counter balance to compensate for the missing blade and therefore are equally bulky as the other. Three blade design is more dynamically stable than two blade, because the two blade model creates more fluctuating forces against the yaw mechanism. In general two blades is also noisier than three blades. Three blades is therefore considered the best solution for HAWTs. They produce more energy and run smoother, than the other models. They are also considered more aesthetically pleasing. In figure 22 three different models of blade numbers is visualized. (Gipe 2004, 102-105.)

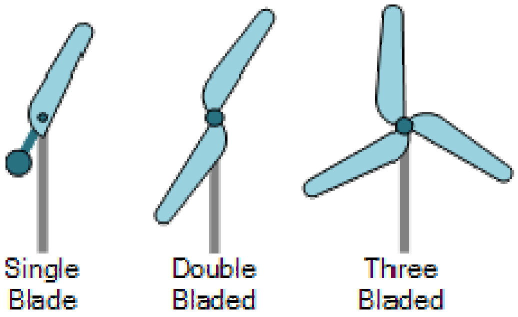


FIGURE 22 Different number of blades on a HAWT (Wind turbine design.)

Since blades catch the wind they need to be made from correct materials. In the past many blade materials have been used. Earliest blades were made from wood and canvas. Later all wood blades became more popular. Wood was easy to carve into desired shape and flexible by nature. Some of the smallest HAWT can still use wooden blades. At the end of 19th century manufacturers became interested in metal blades and some attempts were made, but they never catch popularity. Metal blades suffered from metal fatigue and are also more expensive and heavier than other materials. In the turn of the 20th century fiberglass and other plastic composites started to be used for blade material. Fiberglass is inexpensive, strong and durable material. Fiberglass blades are currently most common in small HAWTs. Some blades are even reinforced with carbon-fiber, to add extra rigidity. (Gipe 2004, 107-111.)

In small-scale HAWTs the blades are often connected to the hub rigidly, but sometimes the blades can be attached to a pitch-control. Pitch-control is used to turn the blade along its longitude axis. This is done to control power output and protect the turbine. Pitch-control is widely used in large-scale turbines, but has yet to be spread into small-scale, because of its complicity. (Gipe 2004, 111-112.)

3.2.2 Turning the turbine to face the wind

HAWT needs to be turned to make sure it catches the wind, this is also known as yawing. Yawing can be done actively or passively. Passive-yawing is done in HAWT with the tail vane as seen in figure 20. Tail turns the rotor upwind with the help of the wind, like with the wind vanes people have on top of their houses. Active-yawing is done by hydraulic or electric motor turning the rotor. They need separate wind vanes to understand what direction the wind blows. Active-yawing is used in medium- and large-scale wind turbines, but they are not that common in small-scale. (Gipe 2004, 90, 93.)

3.2.3 Protecting the turbine from high wind

When wind blows too fast, it can damage the turbine. That is why HAWT needs a way to control the rotor. Small wind turbines can use furling to protect itself. Furling works by folding the rotor away from the wind. In passive furling winds trust to the rotor exceeds the hinges restraining forces and causes it to turn from the wind. The turbine can be folded vertically or horizontally. Figure 23 shows a HAWT furled vertically. (Gipe 1999, 26-28.)

FIGURE 23 vertically furled wind turbine (Gipe 2013b.)

Other way of protecting the rotor is to use pitch-control to cause stalling to the blades. When the blade stalls it loses lift and thus limits the rotation speed. Pitching is considered to be more reliable than furling, but is more expensive. Stalling can occur without the need for pitch-control. This happens when the generator holds the rotor at constant speed and wind speed increases over the operating limit, causing the blade to lose aerodynamic performance. This requires power to operate and will not work during power outage. (Gipe 2004, 135-139.)

Braking is another mean of slowing down wind turbines. Brakes are often placed on the main shaft, to minimize risk for any failures. Brakes can be mechanically, electrically or hydraulically operated. Brakes should operate in such way that they are braking when no force is applied to release them. Brakes are not fool proof and should always be paired with some other means of limiting rotor speed. Brakes are also important for maintenance reasons. Brakes ensure that maintenance does not need to relay on calm wind conditions to do service. (Gipe 2004, 140-145.)

3.2.4 Turning rotation in to electricity

The rotor angular velocity is transferred to the generator through a gearbox or directly along the main axis. Direct drive is mainly used on the smallest wind turbines. Gearboxes are used to increase rotation speed, so that the rotor does not need turn as fast and the generator can be smaller. In small wind turbines gearboxes have usually one or two stages. Bigger machines may require even more stages to operate sufficiently. (Gipe 2004, 114-119.)

Generators role is to convert mechanical energy into electricity. Generator consists of coils of wire, a magnetic field and motion between the two. Power output of the generator is dependent on wires diameter and length, power of the magnetic field and the speed of motion. Maximum current can be altered by chancing wires. Voltage changes when the magnetic field or the speed of motion is altered. Number of wire coils also influences voltage. Electric power of the generator is in relation to current and voltage. A generator can produce alternating current (AC) or direct current (DC). Generator basic components are rotor and stator. Rotor turns with the axel and stator stays in place, this creates the motion between the coils and the magnetic field. (Gipe 2004, 119-121.)

Small wind turbines use number of different type of generators. Almost all turbines under 7 kW use permanent magnet generators (PMG). PMGs create electricity without the need for external power and are relatively simple. Model of a radial PMG is presented in figure 24. In the bigger generators PMG becomes too expensive, because they are hard to produce and material cost are high. Bigger generators relay in induction generator. Induction generators can be synchronous or asynchronous, this means that the generator operates either in or out of synchrony with the power that creates the magnetic field. With the induction generator both stator and rotor consist of coil wires. Induction generators are cost efficient and lose very little energy in the conversion. (Lawson 2012.)

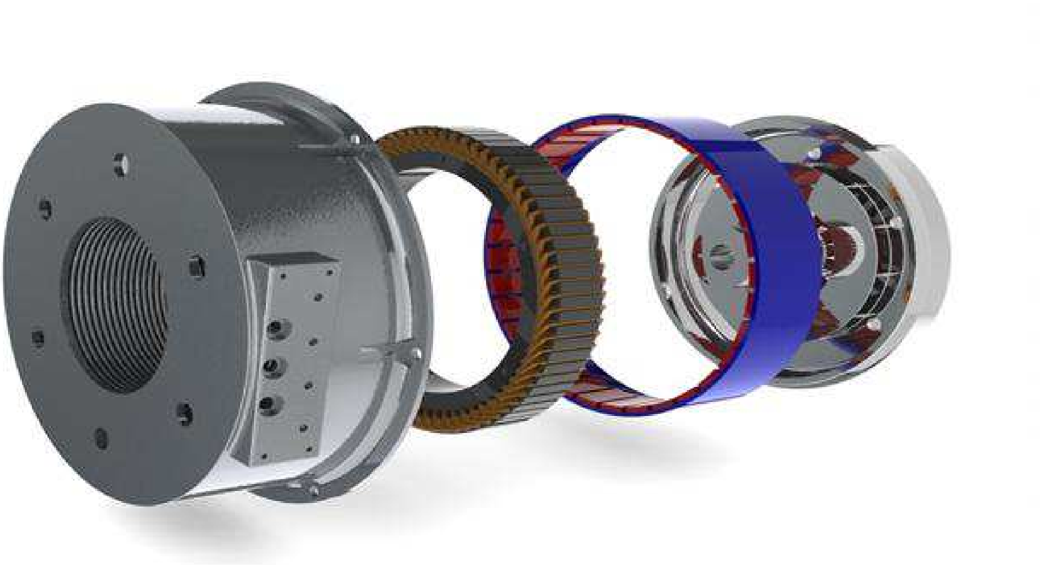


FIGURE 24 Permanent magnet generator model. (PM Generators 2015.)

3.3 Comparison of technologies

Differences between the three main wind turbine types are significant. They affect cost, efficiency, operation, power output and installation of the wind turbine. The main differences are listed in Table 1. Need for yawing is a clear example of differences between HAWT and VAWT. VAWTs do not need it and HAWT cannot operate without it. The choice of yaw mechanism affects HAWTs price and operation costs. VAWTs omni-directionality helps its positioning in difficult wind conditions. (Bernhoff et al. 2006.)

Axis direction do not affect just the rotation of the blades, it also dictates generator’s location and need for tower. VAWTs can place generator on the ground, but HAWTs cannot. This gives some benefits to VAWT, like easier maintenance and installation. Also the generator can be built without any weight restrictions and it helps efficiency and cost. HAWTs require a tower to support the rotor and the nacelle. Placing all that weight on top of a tower requires bigger foundations for HAWTs. This is not all bad, because lifting the turbine higher increases the possibility for better wind. (Bernhoff et al. 2006.)

TABLE 1 Differences between the models of wind turbines (Bernhoff 2006.)

	Savonius	Darrieus	HAWT
Axis direction	Vertical	Vertical	Horizontal
Yaw mechanism	No	No	Yes
Pitch mechanism	No	Optional	Optional
Noise	Low	Moderate	High
Solidity	High	Low	Low
Generator position	Ground	Ground	Top of tower
Blade load	Low	Moderate	High
Self-starting	Yes	Problematic	Yes
Tower	No	Optional	Yes
Foundation	Small	Moderate	Large

Blade design varies between the three types. HAWTs blades are often aerodynamically shaped and need to be connected from one end. This causes production costs to rise. Darrieus turbines often have the simplest blade model, which in some cases can be even extruded. Savonius turbine blades intercept most wind, because of its solidity. The other two generally catch less off the wind that passes through their swept area. VAWTs have less constant torque than HAWTs, this is due to changing angle of attack. Fluctuating torque causes tress to drive-gear and blades. Self-starting is most problematic for Darrieus-style turbines. HAWTs are best at self-starting, as long as blades point toward prevailing wind. (Bernhoff et al. 2006.)

Wind conditions at the planned site affects the choice of turbine. VAWTs work better than HAWTs when wind chances direction and blows irregularly. That is why they are more commonly used in urban areas. HAWTs are usually a better choice when they can be lifted higher than the surrounding obstacles, securing steadier wind conditions. VAWTs often have lower cut-in wind speeds limits than HAWTs, this helps in the positioning of the turbine. (Abraham 2014.)

3.3.1 Comparing turbine performance

Wind turbine performance depends on wind speed, swept area, air density and power coefficient as seen on equation 1. Wind speed is the most important factor in turbine performance because it affects to the power of third, but if the coefficient is not big enough, all the winds energy is lost. (Bernhoff et al. 2006.)

$P = \frac{1}{2} C_p \rho_{air} A v^3$ EQUATION 1

C_p = Coefficient of Power
ρ_{air} = Density of air (kg/m^3)
A = Swept area of turbine (m^2)
v = Speed of wind (m/s)

Wind turbines power coefficient is a function of the tip speed ratio. Tip speed ratio defines how fast the tip of the turbine travels in relation to wind speed as seen on equation 2. (Bernhoff et al. 2006.)

$\lambda = \frac{\omega R}{v}$ EQUATION 2

λ = Tip speed ratio
ω = Rotor rotational speed (1/s)
R = Radius of the blade (m)
v = Speed of wind (m/s)

The power coefficient is the most significant value of a wind turbine, it shows how much wind the turbine can catch. Engineer Albert Betz published in 1919 a theory for maximum coefficient of power. This maximum is called the Betz limit. Betz discovered that with an ideal wind turbine in an ideal conditions the maximum coefficient of power ca not exceed the value of 0,593. This implies that not all of the wind is possible to be turned into power. (Carriveau 2011, 19-25)

Tip speed ratio (TSR) is important, because it tells how fast the blade has to turn to produce optimal power. If the rotor turns too slow it does not catch as much wind as it could and when it turns too fast it creates too much drag. This shows in figure 25. TSR is affected by blade profile, number of blades and turbine model. Higher TSR often ensures better efficiency, but it has its drawbacks. High TSR can cause blade erosion, noise, vibration and drag losses. (Carriveau 2011, 29-30.)

Even tough Betz limit was invented almost hundred years ago, no current technique can reach it. Three-bladed HAWT comes closest to the limit with maximum power coefficient of about 0,45. Darrieus-style HAWTs can reach almost 0,4 power coefficient. Savonius-type HAWTs do not even reach that with only around 0,15 coefficient of power. The poor efficiency of Savonius turbine, makes it less attractive to buyers. (Nath.)

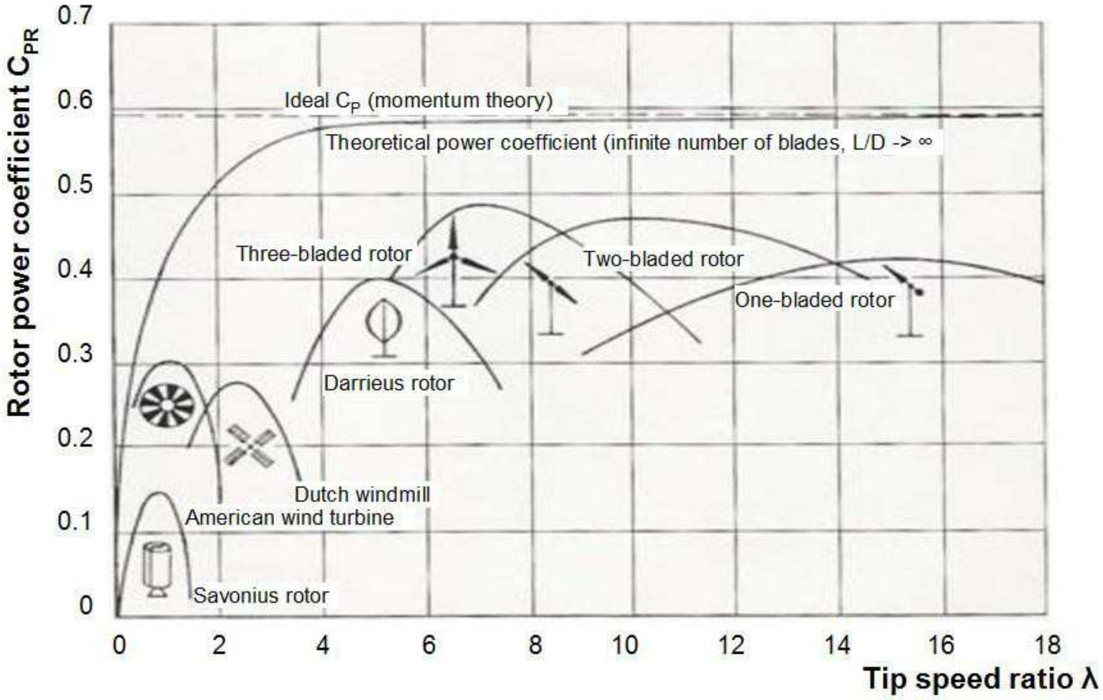


FIGURE 25 Coefficient of power in relation to tip speed ratio (Nath.)

Small wind turbine efficiency is not always as clear as with large-scale. Especially when the figures are given from the manufacturer, the variation can be vast. Some even claim to have broken the Betz limit. In general power coefficient of SWTs is lower than large-scale turbines. Often the main reason is that the SWTs design is not optimized. Even tough standards for measuring exists, they are not yet widely applied. (EWEA 2009a, 133-134.)

3.3.2 Noise emission

Wind turbines produce noise emission when they turn. Aerodynamic noise is produced by blade tips. Another source is mechanical noise from the generator and other moving parts. In general HAWTs produce more noise than VAWTs, because they run at higher tip speed ratio. Positioning of the drive train components up in the air further promote the spreading of noise emitted by HAWTs. The Savonius-type wind turbine runs at low TSR, this usually makes it the quietest choice. (Bernhoff et al. 2006.)

Specifically small wind turbines produce noise from blade flutter, furling and stalling. They are all different types of aerodynamic noise. Furling and stalling are done to control speed of the rotor. Pitching and breaking can be used to compensate for those systems. Blade flutter is vibration that is caused by aerodynamic forces pushing on the flexible blades. (Broneske 2012.)

3.4 What else does installation require

Wind turbines cannot operate on their own. They require support structures and auxiliary electronics. Depending on what type of turbine is selected, different size of foundations is needed. Also need for a tower depends on the wind turbine. Electronic equipment varies between different installations.

3.4.1 Tower

Horizontal-axis wind turbines require a tower to lift them of the ground. Also some models of the Darrieus-type vertical-axis wind turbines need one. Often with large-scale turbines the tower comes included with the product. In small-scale turbine projects there is more freedom to choose, what type of tower fits the installation. Towers can be freestanding or guyed. Lattice and monopole structures are used for the main part of the tower, as seen on figure 26. Tower needs to be high enough to keep the blades of the ground. To provide best conditions for the turbine, tower should be taller than surrounding objects. For safety aspect blade tips lowest point should be higher than 2,5 meters. Another important factor for tower is that it needs to be able to withstand all the forces that might affect it. Also servicing should be considered when selecting a tower. (Gipe 2004, 147-150.)

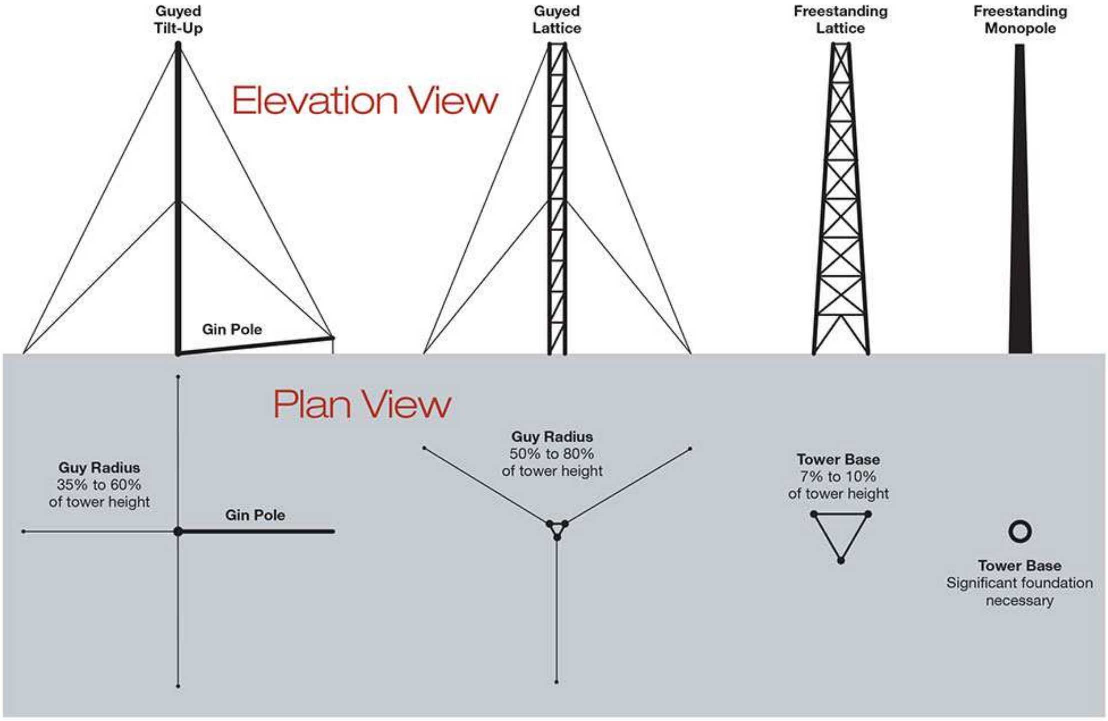


FIGURE 26 Different type of wind turbine towers. (Butler 2014.)

Self-supporting, or also known as freestanding, towers require large foundations to support all the weight and stresses wind turbine might encounter. That is why they also need to be sturdier, than guyed towers. Freestanding towers can be made with lattice or monopole construction. Lattice towers are little pit cheaper than monopoles. Some consider monopoles to be more aesthetically pleasing. Both usually require crane for installation. (Gipe 2004, 147-150.)

Guyed towers are more commonly used with small-scale turbines. They rely on cables, which are connected to ground anchors, to support the main tower. The main tower itself can be made with monopole or lattice structure. Guyed lattice towers are very popular, because they are the cheapest option. They are widely used in the telecommunication industry, which helps to lower their cost. Smaller foundations can be used for the guyed towers. Even though foundations are smaller, their footprint is larger than self-supporting towers. Bigger footprint means that installation location needs more space. Table 2 compiles the most common properties of towers. Tilt-up towers rely on guywires for support. Tilt-up towers are usually used in very small turbines, because they do not require a crane for installation. (Gipe 2004, 147-150.)

TABLE 2 Properties of wind turbine towers. (Butler 2014.)

	Tilt-up	Guyed lattice	Self-supporting lattice	Self-supporting monopole
Footprint	Largest	Fairly large	Small	Smallest
Foundation	Moderate	Minimal	Large	Largest
Cost	low	moderate	High	Highest
Installation	Built on the ground; no crane needed	Crane	Crane	Crane
Turbine size	<5 kW	< 20 kW	< 50 kW	all sizes
Other	Best on reasonably level ground; Can be lowered to service turbine	Must climb to service turbine	Must climb to service turbine	Usually must climb to service turbine, although some are available with hydraulic tilting option

3.4.2 Foundation

All types of wind turbines require some sort of foundations that hold it in place. Foundation size is dependent on size and model of the turbine, type of the tower, locations soil material and wind conditions. Most commonly foundations are made from concrete and are steel reinforced. Tower or turbine manufacturers often recommend the size for the foundations. For example a 24 meter guyed tower with a 5 kW HAWT, would need approximately 1 m^3 main foundation and at least three 1 m^3 anchors. Similar turbine with a monopole setup would require at least 10 m^3 foundation to handle all the stresses. If foundations are not planned properly it can have catastrophic consequences, as seen on figure 27. There are different type of anchors for different soil types. Concrete anchors are most common, other models like screw, expanding and rock anchors can be applied only to suitable soil. (Gipe 2004, 305-312.)

FIGURE 27 Catastrophic failure of a wind turbine foundation. (Miceli 2013.)

3.4.3 Power electronics

Every wind power system requires some type of power electronics. Depending on what type of installation is used, different types of power electronics is needed. Off-grid system requires batteries and charger. Grid connected system needs inverter to moderate the produced electricity. For both systems a wind turbine controller is necessary to prevent damage to the wind turbine and maximize production. Controllers can convert DC voltage to the preferred voltage. They can monitor peak-power to be able to shut-down the system for safety. Controller can operate also as a rectifier that turns AC to DC. (Gitano-Briggs 2010.)

On- and off-grid applications need to have power conditioning equipment. They are required, because wind power has tendency to fluctuate. Power conditioning can be divided in to four basic parts: current conversion, frequency regulation, voltage regulation and AC sine curve regulation. Not all of the four are needed in every installation, it depends on the project. Current conversion is used to convert DC power to AC power. Most of the modern electronic appliances require AC power to operate. Frequency regulation is used to make sure that the frequency of the electricity is correct. In Europe 50 Hz is the standard electricity frequency. Voltage regulation is needed to maintain steady power output. Some equipment can operate with low-quality electricity, but for example televisions and computers require consistent voltage and smooth sine curve. Sine curve regulation shapes jagged AC waves in to required smoothness. (Balance-of-System Equipment Required for Renewable Energy Systems.)

Inverters are meant for power conditioning. They transfer DC power to AC power and during that process regulate frequency, voltage and quality of the output electricity. Inverter needs to be designed to work with the installed electricity grid. Grid-tied inverters can be automated to recognise grid properties and integrate to it. It is always best practise to contact grid owner, to ensure compatibility of the products. An example of a 6 kW inverter can be seen on figure 28. (Joka miehen opas pientuulivoiman käyttöön, 13-14.)

FIGURE 28 ABB's 6kW inverter. (PVI-6000-TL-OUTD-W.)

Off-grid applications often need a charge controller and batteries to reliably store power. Power stored in batteries can provide energy when system is other vice shutdown. In small systems deep-cycle lead-acid batteries have been used for the last decade. They are made for storing and discharging electricity multiple times. Automotive batteries are not as reliable and therefore should not be used. Capacity of the batteries should always be planned case by case, to meet consumption needs. Batteries are usually made from lead-acid, because weight is not an issue, but some manufacturers are trying to bring other materials to market, such as Lithium-ion batteries. For example Tesla Motors is bringing their Powerwall battery-system, which relies on their expertise on lithium-ion batteries with electric-cars. They are more compact and lighter, but as long as they cost more they have hard time competing. When comparing cost of batteries it is also important to analyse life-expectancies and available capacities, because they affect life-time cost. Tesla has already cancelled its 10 kWh back-up power system that uses nickel-cobalt chemistry, because the 500 cycle life- expectancy did not interest byers. They now only sell the 6,4 kWh nickel-manganese batteries that last 5000 cycles. (Balance-of-System Equipment Required for Renewable Energy Systems; Tesla Motors 2016.)

Wind turbine has to be under a load, when it is operating, or it can be damaged. This causes a need for a dump load that can replace the power load of the system. This can happen when batteries reach full charge and no other consumption is on. Grid-connected systems usually do not have this problem, because they can dump excess power to the grid. A dump load is an electric resistor, which produces heat. The heat produced by dump load can be used for heating water. (Windy Nation Inc.)

Wind turbine electronics require also safety equipment. Grounding is very important for all electronic equipment, it protects from lightning strikes and equipment failures. All metal components need to be grounded. Surge protection provides protection to your system from voltage spikes. Safety disconnects are needed to protect against power surges and equipment malfunctions, but are also good for shutting down the system for maintenance. (Balance-of-System Equipment Required for Renewable Energy Systems.)

3.5 What special features arctic conditions require

Arctic region experiences vast variation in weather conditions during a year. Cold climate impacts wind turbines by icing and freezing components. This effects operation time, annual energy output and operation cost. Some estimates state that there could be up to 40 GW of potential wind power in cold climate areas. Cold climate components have been developed in the past decade, to meet the harsh conditions. (Baring – Gould – Cattin – Durstewitz – Hulkkonen – Krenn – Laakso – Lacroix – Peltola – Ronsten – Tallhaug – Wallenius 2011, 10.)

Cold climate is defined as areas where temperatures drop below normal operational limits or icing occurs regularly. In literature cold climate is divided in to two sections: Low temperature climate and icing climate. Low temperature climate areas are places where temperature falls below standard wind turbine operation. Icing climates on the other hand are areas where icing events occur. (Baring et al. 2011, 11.)

Area is considered a low temperature climate (LTC) site when, minimum temperatures are under -20°C for at least nine days or long term average temperature is below 0°C. LTC can affect the turbine and component materials, by making them brittle. Low temperature cold starts can be difficult for wind turbines. Oils and lubricants need to be LTC compatible or they may lose viscosity. If the Turbine components are heated, to cope better with LTC, it increases internal energy use. (Baring et al. 2011, 11-12, 16.)

Build-up of ice and snow on components that are exposed to elements is called atmospheric icing. It can be divided into two different types that affect wind turbines: in-cloud icing and precipitation icing. In-cloud icing is caused when water droplets hit the cold surface and freeze immediately. Precipitation icing happens when freezing rain or wet snow hits the turbine and freezes into ice. Icing event has two different phases. First in meteorological icing weather conditions changes in to favourable for ice formation. Next the instruments freeze and are effected by ice, this is called instrumental icing. Figure 29 illustrates the timeline of icing. International Energy Agency has a five stage ice classification. Number one is the mildest with only under 0,5 % of a year effected by icing. Most severe is number five, with over 10 % of the time effected by icing. (Baring et al. 2011, 12-13.)

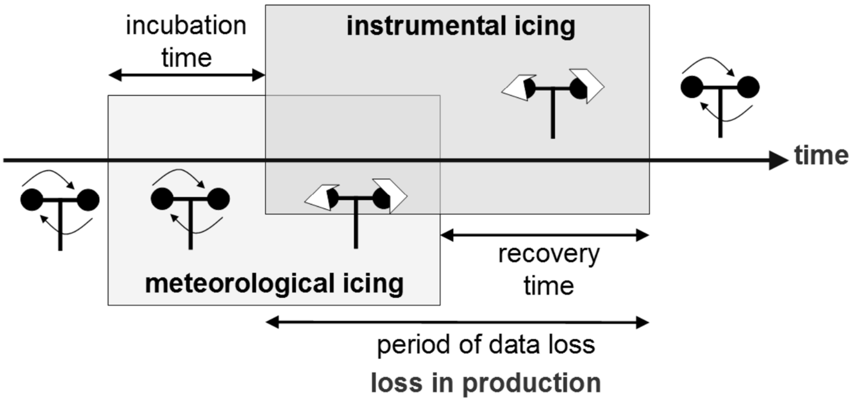


FIGURE 29 Definition of meteorological and instrumental icing. (Baring et al. 2011, 14.)

Icing climate can cause multiple problems for wind turbines. It affects wind data gathering, structural loads, noise level, safety and energy production. Ice build-up on structures can cause catastrophic failures if it is not taken into consideration in planning. Ice on blades reduce their aerodynamic performance and therefore energy yield. It can also cause vibrations in to structures, due to imbalance. Safety issues are caused when ice is thrown from the blades. There are warning signs, for falling ice, around wind turbines, as seen on figure 30. (Baring et al. 2011, 14-17.)

FIGURE 30 Warning signs for falling ice (Baring et al. 2011, 36.)

3.5.1 How to know if cold climate affects installation site

To help estimate icing conditions on a planned site, there is icing atlases that provide mathematical calculations on annual icing. They are very similar to wind atlases. For example the Finnish Icing Atlas shows the number of hours when intensity of icing is greater than 10 g/m/h. This is based on the ISO 12494:2001 standard, where ice is collected from a 3 cm diameter and 1 m tall cylinder and measured. The Icing atlas also provides an estimated annual production losses for a 3 MW wind turbine. Similar data for Norway and Sweden can be obtained from Kjeller Vindteknikk's website. More substantial way of estimating icing conditions is to measure it for a year. This requires specific instruments, designed to be used in cold climates. Measurements need to include humidity, temperature, wind speed, wind direction and precipitation. Example of an icing map can be seen on figure 31. (Ronsten – Wallenius - Hulkkonen – Baring - Gould – Cattin – Durstewitz – Krenn – Laakso – Lacroix – Tallhaug – Byrkjedal - Peltola 2012,. 10-20, 23-28.)

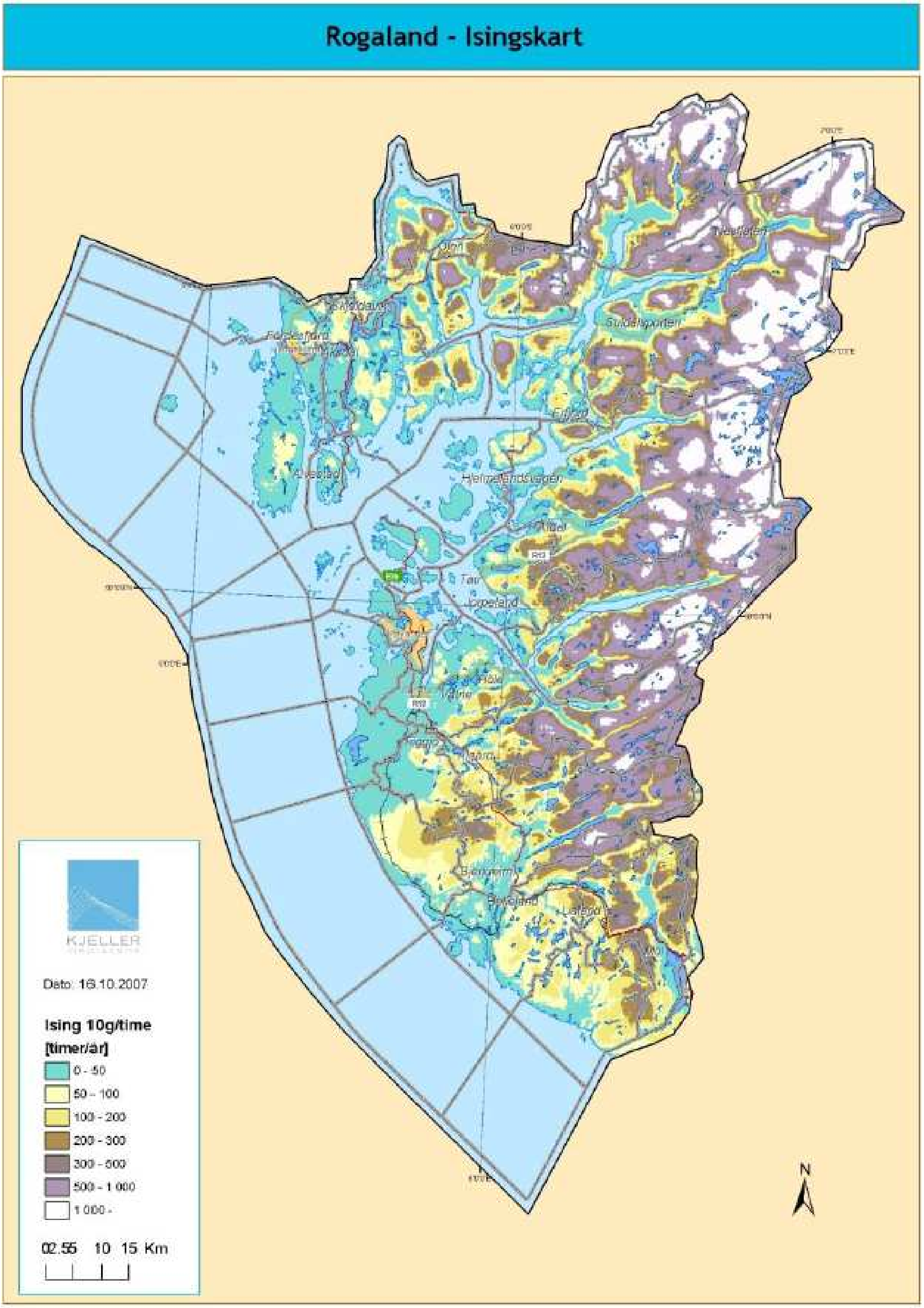


FIGURE 31 Icing map of a region in Norway. (Ronsten et al. 2012, 15.)

3.5.2 Cold climate technology for wind turbines

Cold climate conditions require specific materials and control systems to operate reliably. Standard wind turbines are often designed to withstand -20°C temperatures, which is not enough for LTC sites. Cold climates can cause problems in many parts of the wind turbine, like rubber seals and welds. Wrong oils and lubricants can cause damage to parts like bearings and gearbox. In low temperatures wire insulations can become brittle and fracture, causing shorting, if proper materials are not used. Components should be sealed properly to prevent them from drifting snow. Even things like foundations should be built to last cold climates, to prevent from frost damage. It is good practice to select an experienced turbine manufacturer, which has previously supplied turbines to cold climates, to avoid problems. (Baring et al. 2011, 24-28.)

Systems like preheaters can help the operation at cold climates. If possible, the rotor blades should be installed with an anti- or de-icing system. Anti- and de-icing technologies are still in development and mainly offered for large-scale products. Most promising systems rely on electro thermal heating foils, which are embedded in to the blade. There has been research in the field of nanotechnology to prevent ice sticking to blades. This would reduce the need for thawing systems. (Baring et al. 2011, 25-26.)

3.5.3 Cold climate operation and maintenance

Operating and maintaining wind turbine in cold climate is challenging. Icing and low temperatures cause problems for rotor, nacelle, wind vane, tower, foundation and sensors. Cold climate affects power production and shortens the life expectancy of the turbine. Cold climate can cause unnecessary down time, due to incorrect wind measurements. Proper maintenance is key for avoiding damage to equipment. If the system does not have anti- or de-icing, it is vital to check the turbine for icing before restarting in cold climate, to avoid problems. Icing can make the turbine noisier than usually, because it affects the aerodynamic balance of the blade. That is why blades need to be free of ice when operating. (Baring et al. 2011, 30-31.)

3.5.4 How cold climate effects on the efficiency and operation time

Cold climate interrupts normal power production of the turbine. Icing clogs the blades and therefore influences turbine efficiency and operation time. The ice build-up affects the shape and roughness of the blade causing losses in aerodynamic performance. Predicting production losses caused by icing can be done with monitoring type, load, intensity, duration and frequency of icing and comparing the data to weather information. Some predictions of production losses can be done by analysing the Icing Atlas and subtracting the effect of icing from normal production estimates. (Baring et al. 2011, 32-33.)

The choice of turbine affects production in cold climates. For example the choice between stall and pitch control effects a lot in production losses caused by icing. Stall controlled turbine is more effected by light icing than pitch controlled, but with heavy icing the table is turned, as seen on figure 32. (Baring et al. 2011, 33.)

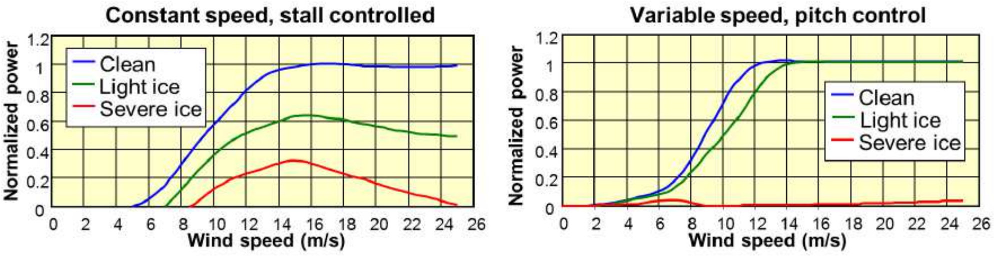


FIGURE 32 Effect of different icing conditions on two types of HAWT. (Baring et al. 2011, 33.)

Cold climate can have also a positive effect on production. Cold air is denser than warm air, for example if you compare 20°C and -20°C air densities, the colder air is about 15 % denser. Since air density correlates directly to power output, wind turbine can produce more at low temperatures. There has been even reports of overproduction, in which generators have overheated and damaged. (Leclerc – Masson 2014.)

3.6 Matureness of small-scale wind turbines

Technology of small wind turbines is still in early stages of development, but great effort towards maternity has been done. Standardisation of products, testing and labelling is progressing and manufacturers are beginning to implement them to production. Some countries, like Denmark and United Kingdom are further along in the proses of maturity. They implemented the IEC-standards as a part of their national regulations. Standards help consumers choose the right product for their situation and build trust to the manufacturer. It is very likely that SWT market will grow in the near future and the level of maturity will follow. At the moment standardised tests can be expensive for small manufacturers, which may slow down its implementation. Also some markets have their own standards, which require separate testing and creates unnecessary costs. It would be simpler, for customers and manufacturers, that there were only one set of standards. (Forsyth – Burch – Boshell – Baranowski 2015.)

The most mature technology in small wind turbines is the horizontal-axis wind turbine. This is due to technological advances in large-scale wind power, which has been implemented into small-scale products. Almost three quarters of the market is dominated by HAWTs. The most important future development in small wind is improving efficiency in challenging wind conditions. Vertical-axis wind turbines might be the solution for that, since they generally work better in those conditions. (WWEA 2016a.)

Consumer labelling can help to increase SWT maturity, as long as it is been widely used. Labelling helps consumers get comparable data of the turbines and it increases understanding and trust towards SWTs. Labelling has also a positive effect on the manufacturing, since it levels the playing field and forces all to test their products. Consumer labels can help SWTs be more interesting to policy makers when they make decisions on energy policies, which can help the SWT market. (Byrne – Cruz - van Dam - Forsyth – Friis – Giroux - Hudnall - Jones– Kawakami - Kim - Larson - Mackinnon - Matsumiya - Ruin - Sabre - Sharman - Summerville - Tokuyama - Whale 2011.)

4 MANUFACTURES OF SMALL WIND TURBINES

Small wind turbines are produced all-around the world. Currently at least 29 countries have some kind of SWT production. Those 29 countries have over 115 companies that produce more than 320 types of SWTs. China is the biggest producer of SWTs, with the capacity to produce over 180000 units per year. Other major producers come from Canada, Germany, the UK and the USA. An effort from the American, Canadian and British Wind energy Associations have been made to enforce the IEC61400 standards for SWT safety and performance to ensure fair market. Most of the SWTs produced are below 5 kW, because the world wide average size for SWTs is under 1 kW. (WWEA 2016a, 6-7; Nordic Folkecenter for Renewable Energy 2014, 2-15.)

A good way to find a reliable and proven manufacturer is to search for one from the small wind certification programs. Currently the American Wind Energy Association has certification program called Small Wind Certification Council (SWCC). The British RenewableUK organization has Microgeneration Certification Scheme (MCS), which covers SWTs and other microgeneration. Those two provide certified products with under 200 m^2 swept area. These certifications can be expensive and are not yet mandatory in every country. The Danish Energistyrelsens Godkendelsessekretariat for Vindmøller has its own certification for SWTs under 40 m^2. Then there is the IEC and AWEA consumer label database that provide certified products, but it currently has only eight products from six manufacturers. If the product is not certified it should at least have CE marking, to ensure that the product is safe to use and allowed to be sold in Europe. A Danish institute called Nordic Folkecenter for Renewable Energy in co-operation with Chinese Wind Energy Association and World Wind Energy Association has gathered a catalogue of small wind turbines, which has more than 300 products. It has a good coverage of the SWT market and provides basic information on the products. (Nordic Folkecenter for Renewable Energy 2014, 15-23.)

4.1 Finnwind Oy

Finnwind Oy is a Finnish technology and consulting company founded in 1993. They produce and market small wind turbines, solar energy systems and islet network products. Their first test SWT was installed in 2005 and customer products shipped in 2008. They currently produce Tuule E200 and C200 HAWTs. The E200 is a grid-connected system and the C200 is an off-grid version. Tuule E200 has rated power of 3600 W with a 10 m/s wind speed. The turbine has a swept area of 20 m2 and starts operation at 2,1 m/s. The Tuule E200 costs about 12500 € without installation. Tuule E200 have been installed in cold climate conditions, as seen in figure 33. (Finnwind Oy, links Tuulivoima -> Tuule C200 - akkujen lataus tuulivoimalan yleisesite.)

FIGURE 33 Tuule E200 with a 27 meter mast installed in Northern Ostrobothnia. (Finnwind Oy, links Referenssit -> Tuule E200 tuulivoimala, Pohjois-Pohjanmaa.)

4.2 Oy Windside Production ltd.

Oy Windside Production ltd. is a Finnish company, which has been producing wind turbines since 1982. First Windside wind turbine was invented in 1976. They have shipped to over 40 countries around the world and even in Antarctica. Their product range is concentrated in VAWT with a power output of 30-2500 Watts. The design of the turbines is based on Savonius wind turbine. The products are mainly meant for charging batteries in remote locations. They are built robust, to withstand harsh conditions. Individual product information can be found from Table 3. (Oy Windside production Ltd, links Yhtiö.)

TABLE 3 Windside production Ltd. wind turbine models and basic information. (Oy Windside production Ltd, links Tuotteet.)

Model	Rated Power [kW]	Weight [kg]	Start-up [m/s]	Max wind speed [m/s]	AEP at 5 m/s MWS [kWh]	Price [€]
WS-0,15B	0,03	38	3,8	40	40	
WS-0,30C	0,06	42	2,8	30	80	4904
WS-0,30Bplus	0,06	45	2,8	50	80	
WS-2City	0,42	120	2	20	700	15990
WS-2B	0,42	550	2	40	700	
WS-2CityG	0,42	170	2	25	700	18000
WS-4B	0,85	800	2	40	2000	49000
WS-4A	0,85	1000	2	60	2000	
WS-12	2,54	6000	2	40	8640	

Windside products are used in many demanding conditions like sand- and snowstorms to produce off-grid electricity. Figure 34 shows a Windside turbine operating in Norway. (Oy Windside production Ltd, links Asiakkaat & Markkinat.)

FIGURE 34 Windside WS-0,15B wind turbine producing power for a police repeat station in Norway (Oy Windside production Ltd, links Tuotteet.)

4.3 Windforce Airbuzz Holding AB

Windforce is a Swedish manufacturer of small wind turbines and hybrid systems. They aim to produce products that provide environmentally friendly energy. Their product range covers wind and solar power. Windforce's Wind turbines produce 0,4-3 kW of power. Other properties can be found from Table 4.The products are aimed at household market and can be bought with different options for On- and Off-grid. Their newest product is the Windflower that is designed to be more appealing for urban installations, as seen on figure 35. (Windforce Airbuzz Holding AB, links Vindkraft.)

TABLE 4 Windforce Airbuzz Holding AB wind turbine products and their properties. (Windforce Airbuzz Holding AB, links Vindkraft.)

Model	Rated Power [kW]	Weight [kg]	Start -up [m/s]	Max wind speed [m/s]	Swept area [m^2]	AEP at 5 m/s MWS [kWh]	Tower height [m]	Price [€]
Windflower	1	28	2	50	3,14		10,5	5330
SpeedX	1	18	3	55	2,54		6	2350
Windstar 400	0,4	22	2,5	50	1,89	840	6	1870
Windstar 600	0,6	25	2,5	50	2,41	1200	6	2830
Windstar 1000	1	28	2,5	50	3,14	1800	6	3570
Windstar 3000	3	70	3	50	7,07	4680	10,5	10000

FIGURE 35 Windflower wind turbine. (Windforce Airbuzz Holding AB, links Vindkraft.)

4.4 WindEn Sweden AB

WindEn Sweden AB is a Swedish wind turbine manufacturer. They currently produce only one type of wind turbine called WindEn 45. It is aimed for farm and small community installations. WindEn 45 produces 45 kW of power, with a 166 m^2 swept area. The product is a three bladed vertical axis wind turbine and it is regulated with stalling. The company promises over 20 year's life span for the product. WindEn 45 is certified for the UK's Microgeneration Certification Scheme and is fully IEC 61400-2:2006 compatible. They provide maintenance service for the product and ensure easily available spare parts. (WindEn Sweden AB, links products.)

FIGURE 36 WindEn 45 wind turbine (WindEn Sweden AB, links products*.)*

4.5 Windon AB

Windon AB was founded in 2007 is a producer of wind and solar energy products. Their wind turbines rated power ranges from 2kw to 30 kW. Additional product information can be found from Table 5. Windon offers normally 5 year warranty, but an extra 5 years is available for purchase. Their products are built to withstand at least -30 to +60 degrees temperatures. They provide spare parts and maintenance for their products. Windon uses synchronous permanent magnet generators, because they require less maintenance and are generally quieter. Their wind turbines can be connected to computer based monitoring system that controls the operation. Figure 37 shows a Windon 20kW installed in cold climate conditions. (Windon AB, links Vindkraft.)

TABLE 5 Windon AB product information (Windon AB, links Vindkraft.)

Model	Rated Power [kW]	Weight [kg]	Start -up [m/s]	Swept area [m^2]	AEP [kWh]	Tower height [m]	Price [€]
Windon 2kW	2		2,5	7,07	2000-8000	12	9200
Windon 10kW	10	1000	1	50,27	7000-22000	12	39500
Windon 20kW	20		1	78,54	14000-43000	24	65600
Windon 30kW	30		1	113,10	35000-74000	24	89000

FIGURE 37 Windon 20kW installed in Wadstena, Sweden (Windon AB, links Vindkraft -> Bilder.)

4.6 Bergey WindPower Co.

Bergey is an American small wind turbine manufacturer founded in 1977, which has been producing wind turbines since 1980. Their products are aimed at homes, farms and small businesses. Bergey wind turbines has been installed in over 100 countries around the world and they are currently one of the leading manufacturers of SWTs. They produce two On-grid and two Off-grid wind turbines. On-grid models are the Excel 10 and 6, which are both fully certified for SWCC and MCS, and also have the consumer label. More information on Bergey wind turbines can be found from Table 6. Bergey wind turbines are designed to withstand temperatures between -40 to +60 degrees Celsius and have been used in Artic conditions. The Excel 10 wind turbine has a 10 year warranty and other Bergey products have 5 year warranty. An example of a Bergey Excel 10 can be seen in figure 38. (Bergey Windpower Co.)

TABLE 6 Bergey Windpower Co. product information (Bergey Windpower Co, links Products.)

Model	Rated Power [kW]	Weight [kg]	Start -up [m/s]	Swept area [m^2]	AEP at 5 m/s MWS [kWh]	Tower height [m]	Price [€]
Excel 10	8,9	545	3,4	38,48	13800	12	28200
Excel 6	5,5	350	1	30,19	9920	12	19500

FIGURE 38 Bergey Excel 10 wind turbine (Bergey Windpower Co, links Products.)

4.7 XZERES Wind Corp

Xzeres Wind is a designer, manufacturer and distributor of SWTs. The company was established in early 2010 and their product line consists of 2,4 kW to 50 kW wind turbines. They provide complete solutions for wind power, including turbine, power electronics, tower and auxiliary components. Their product is said to be highly efficient and have low operation and maintenance costs. They provide 10 year warranty for their products. They have a large network of global dealers that can provide full installation and maintenance service. Their Xzeres 442SR has been proven to be the most efficient turbine ever tested by a third party. Xzeres Skystream 3.7 wind turbines have been installed in over 8000 locations around the world. Skystream 3.7 and 442SR have both full MCS and SWCC certifications. Specific product information can be found on Table 7. All of their products can be connected to computer based monitoring and diagnostic software. The Skystream 3.7 has been designed to be more visually attractive for urban installations, as seen on figure 39. (Xzeres Wind Corp.)

TABLE 7 Xzeres Wind product information (Xzeres Wind Corp, links Wind Turbines.)

Model	Rated Power [kW]	Weight [kg]	Start-up [m/s]	Swept area [m^2]	AEP at 5 m/s MWS [kWh]	Tower height [m]
442SR	10,4	1045	2,5	41	16700	25
Skystream 3.7	2,1	77	3,2	10,87	3420	10
50	51	5558		213,8	100000	

FIGURE 39 Xzeres Skystream 3.7 SWT (Xzeres Wind Corp, links Wind Turbines.)

4.8 Gaia-Wind Ltd.

Gaia-Wind is originally a Danish wind turbine manufacturer, which is currently located in the UK. They have a 20-year experience in designing wind turbines and have installed over 500 turbines worldwide. They produce one type of wind turbine called the Gaia-wind 133. The turbine relies on two blade horizontal-axis design and oversized swept area, to provide high production rate at low mean wind speeds. The Gaia-wind 133 is rated at 10 kW and produces 27502 kWh annually at 5 m/s mean wind speed. The turbine has full MCS certification and is the most productive and quietest wind turbine in the 10-20 kW range tested by MCS. The turbine relies on three different braking systems, passive stall control, mechanical braking and centrifugal activated tip brakes, to provide safe operation. Gaia-Wind 133 has been very popular in the UK, where farmers have installed them on their lands, as seen on figure 40. (Gaia-Wind Ltd.)

FIGURE 40 Gaia-Wind 133 installed at a farm. (Gaia-Wind Ltd. links Events & Announcements -> Image gallery.)

4.9 Shanghai Ghrepower Green Energy Co.

Leading Chinese SWT manufacturer Shanghai Ghrepower Green Energy Co was established in 2006. They have offices all over China and have branched into the USA, Canada, Japan, Italy and Taiwan. Ghrepower has exported products to over 20 countries around the world. They have specialized in the new energy segment and provide wide range of wind turbines to all kinds of solutions. Their wind turbine selection covers power output from 5 kW to 100 kW. Ghrepower is currently only Chinese manufacturer that has SWCC certificate for their wind turbine. Their products are also certified by CE, ETL, G59, CEI 0-21 and IEC 61400. Ghrepower has supplied wind turbines to locations in Russia where temperatures are expected to drop below -45 °C. Figure 41 shows a FD16-5 wind turbine in winter conditions (Shanghai Ghrepower Green Energy Co. 2016.)

TABLE 8 Ghrepower product information. (Shanghai Ghrepower Green Energy Co. 2016, links Wind turbine.)

Model	Rated Power [kW]	Weight [kg]	Start-up [m/s]	Swept area [m^2]	AEP at 5 m/s MWS [kWh]	Tower height [m]
FD5-5	5	190	3	19,6	8890	12
FD8-9.8	9,8	670	3	47,8	17000	20
FD16-19.8	19,8	4000	3	191,1	60100	25
FD16-50	50	4000	3	191,1	80800	25
FD21-50	50	9100	3	363	129100	30
FD21-100	100	9300	3	363	144700	36
FD25-100	100	9500	3	490,9	195000	42

FIGURE 41 FD16-50 Wind turbines in Russia. (Shanghai Ghrepower Green Energy Co. 2016, links Case -> Micro-grid.)

4.10 Average small wind turbine

Comparing wind turbines can be difficult at times, but certification data has helped out a lot. In figure 42 gathered information on SWTs are plotted to visualise average rated power per swept area. Information of over 100 turbines were used to calculate average rated power per square meter. Calculations show that the average rated power is 236 W/m^2. This can be used to evaluate if the product's advertised power rating is correct.

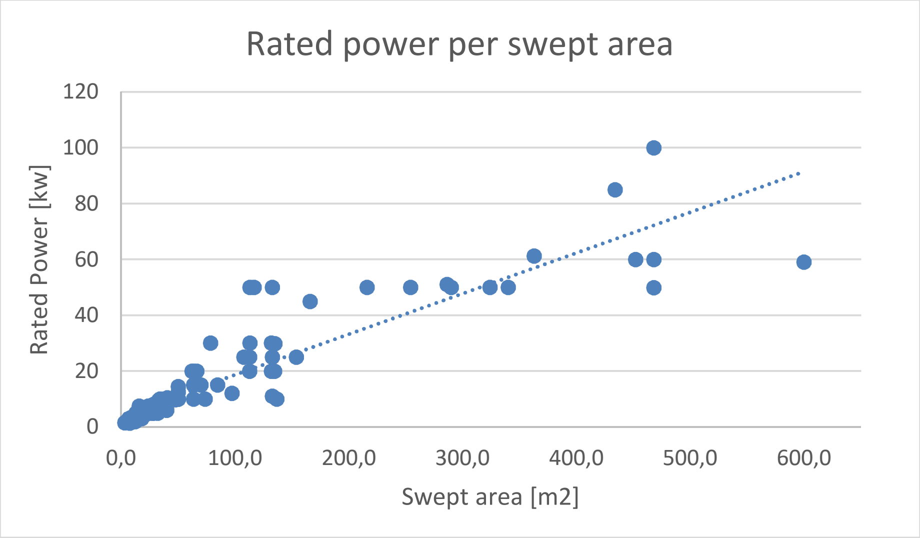


FIGURE 42 Rated Power per swept area

Annual energy output (AEP) is another valuable information to a customer. It can help evaluate how much power the turbine could produce. In figure 43 product specific AEP at 5 m/s annual wind speed have been plotted in comparison against swept area. This gives an idea how large turbine you need to install to meet production expectations. From calculations an average AEP per square meter of 365 kWh/m^2 was achieved.

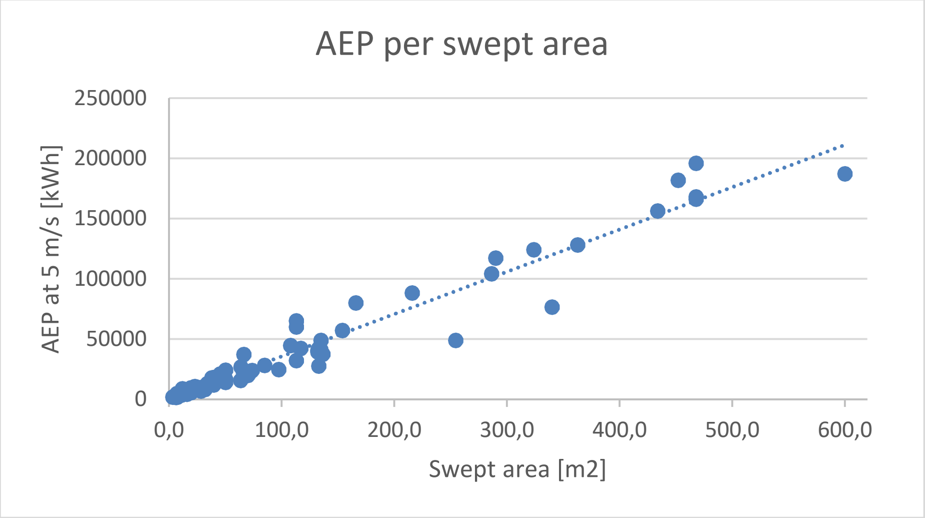


FIGURE 43 Annual energy production per swept area

Comparing certification data of wind turbines we can see that there is a lot of deviation in AEP per square meter. Figure 44 illustrates how much variation there is between products in AEP. The black curve in figure 44 is a calculated average curve. The curve seems to start levelling after 11 m/s, this is because turbines often produce their peak power at that wind speed. From the data we can see that deviation increases with the annual average wind speed. Higher value in AEP per square meter means that the turbine has better efficiency and therefore the turbine should produce more energy.

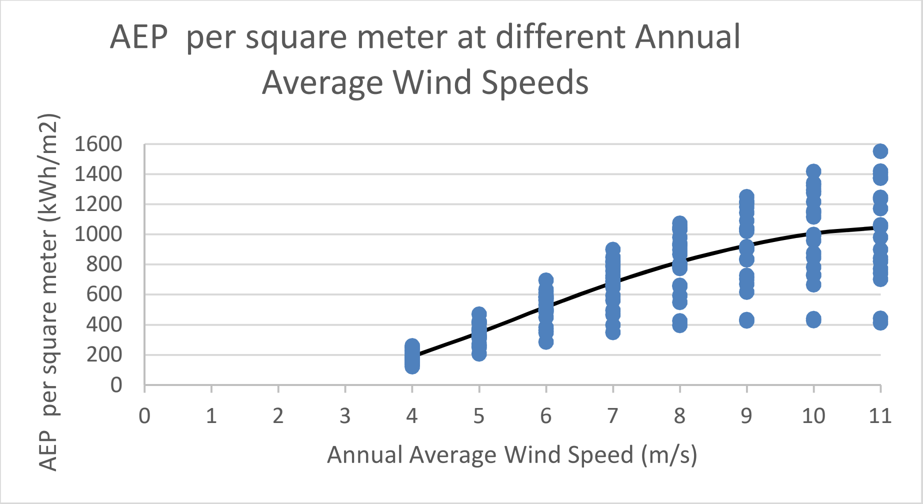


FIGURE 44 Comparison of certified AEP results

5 ECONOMIC ANALYSIS

Evaluation of a wind turbine project includes an economic analysis. One of the most important factors is knowing how much energy the system produces, which means in wind power that you need to know your wind turbines power curve and installation locations wind conditions. Another thing is to know how much it costs to buy, install, operate and service the system. Then you also need to figure out what kind of subsidies or rebates your government can provide. To be able to do an economic analysis you also need something to compare your costs, it can be the price of grid electricity or other means of producing electricity. Often in remote locations wind turbine can replace diesel generator and then the comparing is done against its costs. Figure 45 explains how the cost of wind energy is formed. (Abraham 2014, 17.)

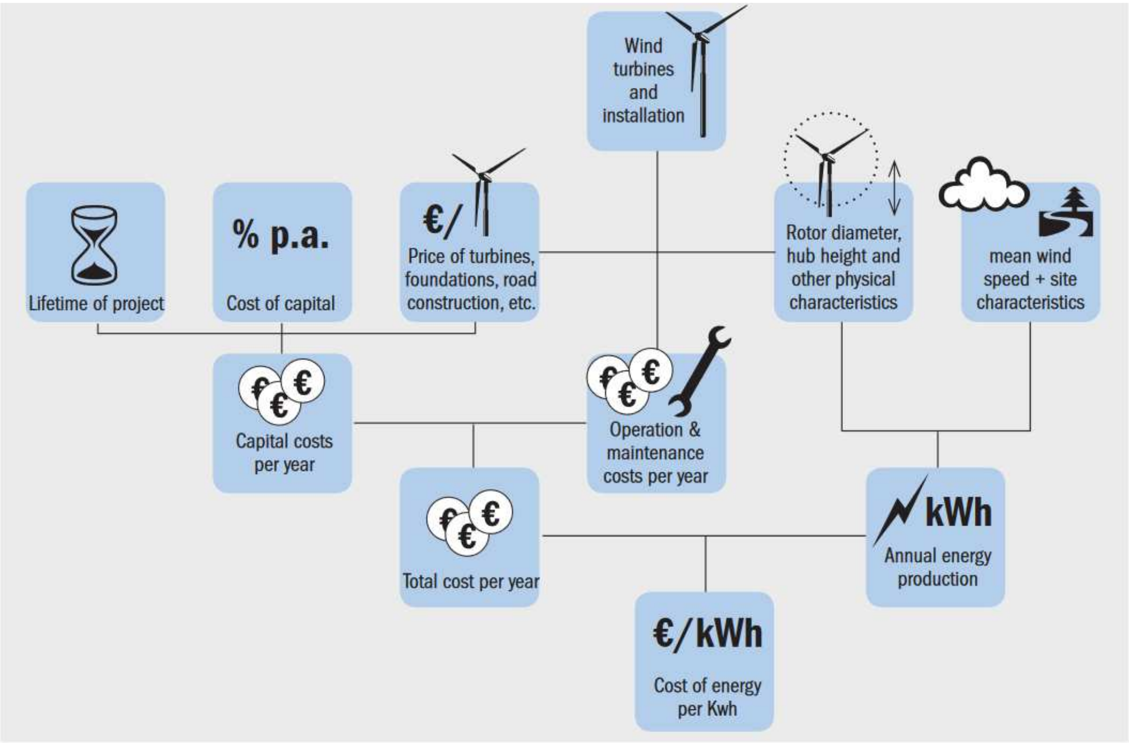


FIGURE 45 The cost of wind energy (EWEA 2009b, 30)

Economic analysis is done with financial calculations. Most common of them are payback period (PBP), return on investment (ROI), net present value (NPV) and internal rate of return (IRR). Another way of evaluating economics that is very popular in renewable energy is Levelized cost of electricity (LCOE). (Abraham 2014, 17.)

5.1 Cost of small wind turbine

Price of a wind turbine provided by manufacturers often does not include all of the components needed to fully install the system, which can make comparing prices challenging. Depending on manufacturer even the tower can be excluded from the price. Foundations are almost every time an extra expense that needs to be added. Shipping costs can be surprisingly high depending on the installation location. Installation costs vary a lot depending on the size of the wind turbine, installation location and difficulty of the installation. Figure 46 represents average cost distribution of a SWT installation in Europe. (Abraham 2014, 22.)

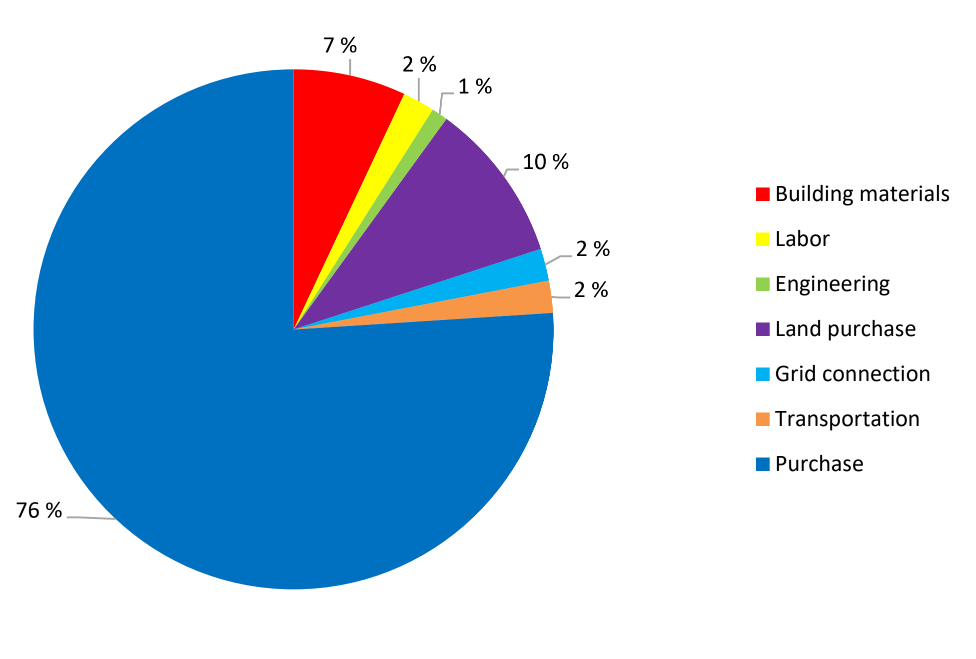


FIGURE 46 Average cost distribution of SWT installation in Europe (Bortolini et al. 2014.)

Total installation costs according to small wind turbine market reports ranges between 1500-8000 €/kW, this gives an idea how difficult it is to compare product cost. In general cost per kilowatt increases when wind turbines power decreases. It is best to gather quotations from products that fit the installation and use those prices to make more detailed assessment of the costs. (WWEA 2016a, 8.)

Shipping can be very expensive if the product needs to be transported long distances. An average transportation costs inside Europe for SWT is around 2300 euros. If the product needs to be shipped across from the USA or Asia, the price can increase significantly. Some manufacturers have designed their products to fit into a single shipping container so that the shipping costs would not be too high. (Abraham 2014, 28; Bortolini et al. 2014.)

Operation and maintenance costs are annual expenses that needs to be extracted from the annual income. Wind turbine operation does not affect profits that much since there is no fuel cost. Maintenance on the other hand is more significant. Maintenance consists of checking, repairing, replacing and servicing the system. It can be expensive if the operation requires a crane. Manufacturers often recommend annual maintenance, but there are some differences between them. According to Danish survey on small wind turbine market maintenance costs on average run for 650 € per year. (Madsen 2015, 12)

Land purchase can be a significant cost factor in the overall installation cost. On the other hand land can be free if its own. Some countries like Sweden demands that wind catchment area is taken into consideration when building wind turbines. Wind catchment area is the land used by the wind turbine to catch wind. In literature a circle with a radius of 2,5 times rotor diameter is considered fair. If some part of the wind catchment area falls into neighbours land some kind of compensation might have to be paid. Sweden uses noise level to determine wind catchment area. Area where noise level exceeds 40 dB is considered wind catchment area and land owners need to be compensated. (Wizelius 2015, 169-170.)

5.2 Income from small wind turbine

Wind turbine produces electricity when wind blows fast enough. The produced electricity is either used on site or transferred to electricity grid. If the production replaces another source of electricity then the reduced spending is counted as income. Often it is more beneficial to replace energy as much as possible, because the price received from the electricity that is fed in to the grid is low. The price depends on the electric company and is often no more than half of what they sell electricity for. So that is why it is very important to design the system to meet demand. (Abraham 2014, 28-30)

Consumer price of electricity combines the price of electricity, transmission fees and taxes. Electricity price tends to fluctuate hourly, depending on supply and demand. To compensate it the Nordic electricity markets have been combined together in the 1990’s, to make the Nord Pool electricity market. This means that electricity can be sold and bought between Nordic countries. In the last five years also Baltic countries have been accepted as a part of the Nord Pool market. Average cost of electricity in the Nord Pool market in 2015 was 21 €/MWh. The price of electricity transmission is set by the grid owner. The transmission fee changes in every location and is higher in remote areas than in rural areas. In Finland an urban family home that consumes 5000 kWh annually transmission fees are about 50 €/MWh. In Finland taxes are also a major factor in the consumer price of electricity. There is two types of taxes electricity tax and value-added tax and they make up 34 % of the electricity price. Currently electricity costs between 12 and 15 cents per kWh depending on annual usage. Figure 47 shows how cost of electricity has developed in Finland since 1997. In 2015 Swedish households paid 18,7 cents per kWh and Norwegian household 14,3 cents per kWh on average for their electricity. (Energiateollisuus 2015; Nord Pool.)

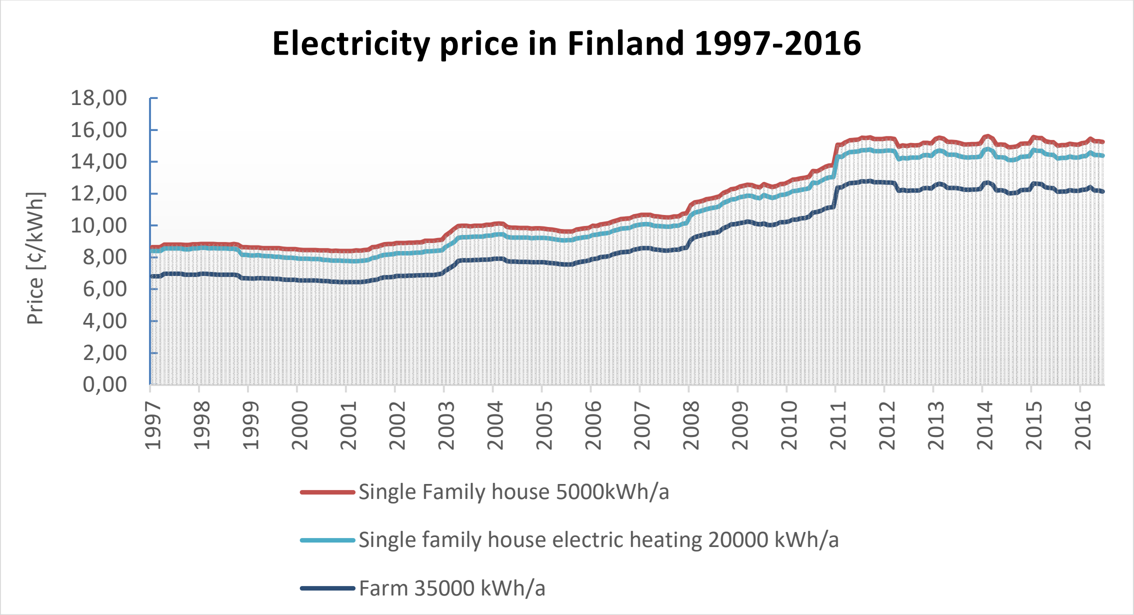


FIGURE 47 Development of electricity price in Finland in 1997-2016 (Energiavirasto 2016.)

If there are available any government subsidies or rebates then they can be a source of income as well. For example some countries offer feed-in-tariffs, which courante a set price for the sold electricity. Also a popular subsidy model is tax credits, where government deducts taxes in correlations to the amount of electricity produced. These systems can make an unprofitable investment be economically viable and are government's way of backing renewable energy development. (Abraham 2014, 30-31)

5.3 Economic calculation methods

5.3.1 Payback period

Payback period can be understood as the time it takes to payback the initial investment of the system. The PBP is a very common way to evaluate if an investment is profitable. Equation 3 shows the calculation method for the PBP. (Abraham 2014, 32-33)

$$Payback\ period = \frac{Investment\ cost}{Annual\ net\ cash\ flow} \qquad \text{EQUATION 3}$$

Typically under 10 year PBP is considered reasonable and under 5 years is great result. In some cases as long as the system pays back in time of the systems life expectancy it is considered investable. This can happen when a new technology is helped to the market. If the system does not pay back in its lifecycle it is really hard to justify. (Abraham 2014, 33)

5.3.2 Return on investment

Return on investment calculation gives out a presentence of return in relation to investment. This can help to understand if the invested capital will rise enough to be viable. The ROI can be calculated with equation 4. (Abraham 2014, 33)

$$ROI = \frac{Gain\ from\ investment - Cost\ of\ investment}{Cost\ of\ investment} \qquad \text{EQUATION 4}$$

Comparing different investments can be done with ROI calculations, but it is not completely reliable because it does not take in count the time. A better solution is to use discounted ROI. It uses discounted net present values instead of gains and costs, which means that it takes in to account the depreciation of money over time. When lifecycle is similar then ROI is very easy and simple to use. A higher ROI is better than a lower ROI and a negative ROI means that the investment is not viable. (Abraham 2014, 33.)

5.3.3 Net present value

Net present value is an economic calculation method that takes into account the inflation. The NPV sums the calculated present values of cash flows. It can be used to evaluate investments profitability over time. When the NPV is negative the investment is not profitable and should be discarded. Positive NPV on the other hand indicates that the investment is viable. Discount rates varies between investments, but is often in the range of 5-10%. For renewable energy investments a discount rate of 6% is considered a good value. (Abraham 2014, 33-34.)

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \qquad \text{EQUATION 5}$$

C_t = Net cash flow in a specific period
t = year of operation (0, 1, 2…n)
n = investment time
r = discount rate

5.3.4 Internal rate of return

Internal rate of return is based on NPV and is the discount rate that gives a value of zero for NPV. This means that there is no need to make an educated guess for discount rate, but the calculations gives a value for it and then it can be compared to other results. A higher IRR adds more value for the investment. IRR should always be at least higher than the interest rates you can get for the money elsewhere. The IRR equation is almost the same as the NPV, but the discount rate is replaced with IRR and the sum needs to equal to zero, as seen from equation 6. (Abraham 2014, 34.)

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} = 0 \qquad \text{EQUATION 6}$$

5.3.5 Levelized cost of electricity

Levelized cost of electricity uses NPV calculations to compare total project costs to electricity output. Both costs and electricity output is discounted to present values, this ensures that they are on the same reference point. Costs consists of investment, operation and maintenance costs over the whole operation period. The LCEO method does not take into consideration any feed-in-tariffs, tax-reductions or any other income. This means that it only gives a value that can be compared to other sources of electricity. Normally LCEO values for renewable energy sources range from 0,1 €/kWh to 0,25 €/kWh and for fossil fuels around 0,06 €/kWh. If the production replaces consumption then LCOE should be compared to grid prices. The LCOE is calculated with equation 7. (Kost - Schlegl – Thomsen – Nold – Mayer 2012, 8.)

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+r)^t}} \qquad \text{Equation 7}$$

I_0 = Investment [€]

A_t = Annual total costs [€]

M_{el} = Annual electricity output [kWh]

r = discount rate

n = investment time

t = year of operation (1, 2, 3…n)

Forecasts done in Fraunhofer institute indicate that LCOE from large-scale wind power will be under fossil fuel LCOE by 2020. Solar panels are expected to undercut fossil fuels by 2025 as a cheaper electricity source. (Kost et. al 2012.)

5.4 Example calculations

In order to study SWTs economic feasibility four different size products were selected. All selected SWTs are certified in one of the certification schemes. They represent four different size categories, with power outputs between 2,1 to 50 kW. The products were chosen, because they are popular and have data easily available. Table 9 provides information on the chosen wind turbines.

TABLE 9 Product information on the selected wind turbines (Xzeres wind Co.; Bergey Wind Power Co.; Solid Wind Power A/S; Endurance Wind Power Inc..)

Manufacturer	Xzeres wind Co.	Bergey Wind Power Co.	Solid Wind Power A/S	Endurance Wind Power Inc.
Model	Skystream 3.7	Excel 10	SWP-25	E3120
Rated power [kw]	2,1	8,9	25	50
AEP at 5m/s MWS [kwh]	3420	13800	57000	117000
Swept area [m2]	10,9	38,48	154	290
Rotor diameter [m]	3,72	7	14	19,2
Start-up wind speed [m/s]	3,2	2,5	2,5	3
Cut-off wind speed [m/s]		20	25	25
Design temperature	-40°C/+50°C	-40°C/+60°C	-20°C/+55°C	
Noise level [dB] (ws; distance to hub)	41,2 (5m/s; 60m)	42,9 (5m/s; 60m)	87,7 (8m/s; 0m)	44,5 (5m/s; 60m)
Turbine model	HAWT 3-blade	HAWT 3-blade	HAWT 3-blade	HAWT 3-blade
Generator	DD PMG	DD PMG	asynchronous generator	asynchronous generator
Tower [m]	10	18	18	24
IEC 64100-2 Class	II	II	III	III
Consumer label	Yes	Yes	Yes	No
Certification	SWCC, MCS	SWCC, MCS	MCS	SWCC

Power curve data for all of the SWTs was easily available, from the certification reports, and the values provided should be accurate since they comply with the certification rules. Power curves were used in the economic calculations to get accurate annual energy production values. Power curves are corrected to an air density of 1,225 kg/m^3. Figure 48 consists of the power curves for all of the wind turbines.

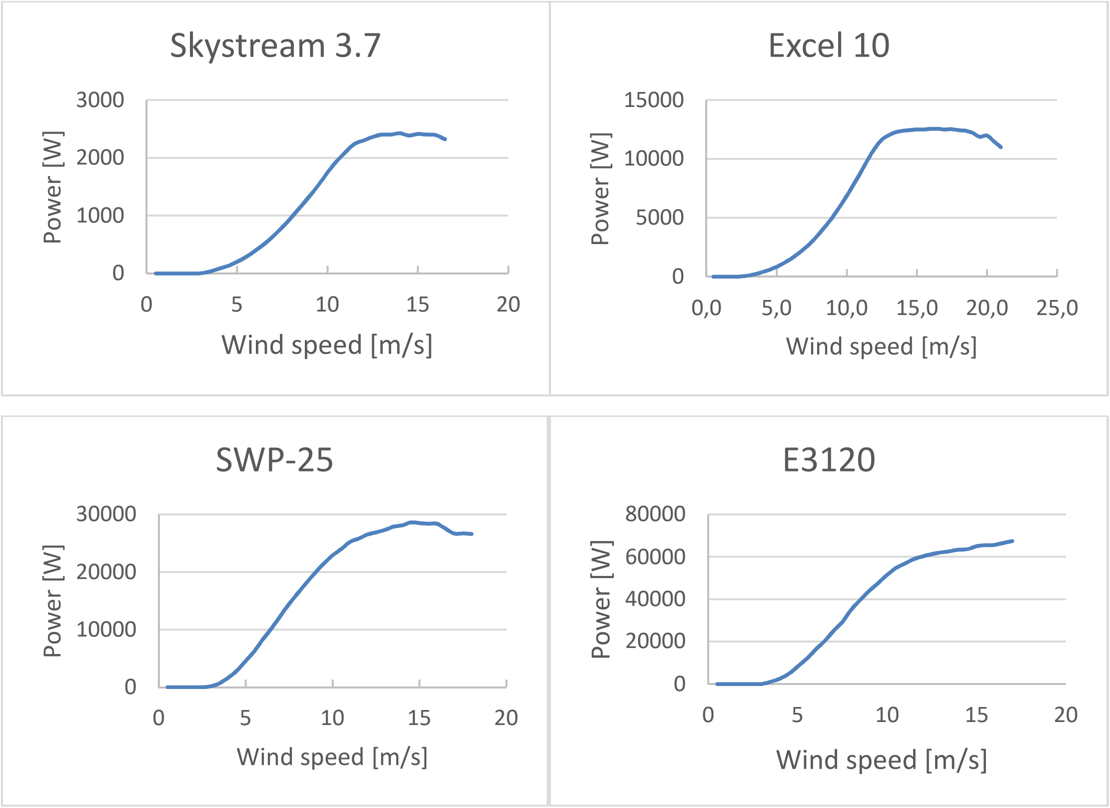


FIGURE 48 Power curves for the SWTs used in calculations (Xzeres wind Co.; Bergey Wind Power Co.; Solid Wind Power A/S; Endurance Wind Power Inc.)

Another important factor for selecting these wind turbines was that prices for them were readily available. The prices included only the wind turbine and the auxiliary components needed for the system. The cost of foundations, labour, designing, transport and grid connection were done based on the average percentages for SWT installations, as seen in figure 46. Cost for land was set to zero, because SWTs are often installed on pre-owned land and it therefore does not cost anything extra. In the calculations wind catchment charges were set to zero, because own land was considered large enough that it would not affect neighbours. The installation costs are only rough estimates and should only be used as a guide. Annual operation costs are estimates based on the Danish survey values (Madsen 2015.). Costs used in the economic analysis are listed in Table 10.

TABLE 10 Costs of the chosen SWTs (Backyard Energy products; Nordic Folkecenter for Renewable Energy 2014; Maden Eco Ltd.; Switched On Energy ltd.)

Model	Skystream 3.7	Excel 10	SWP-25	E3120
Purchase price	11 000,00 €	28 000,00 €	110 000,00 €	250 000,00 €
Building materials	1 000,00 €	2 500,00 €	9 000,00 €	22 000,00 €
Labour	300,00 €	750,00 €	2 000,00 €	6 000,00 €
Engineering	200,00 €	500,00 €	1 000,00 €	3 000,00 €
Grid connection	500,00 €	750,00 €	2 500,00 €	3 500,00 €
Transportation	1 500,00 €	2 500,00 €	3 500,00 €	5 500,00 €
Total installation	14 500,00 €	35 000,00 €	128 000,00 €	290 000,00 €
Annual operation & maintenance	300,00 €	600,00 €	940,00 €	1500,00 €

Wind values for the calculations are based on Weibull distribution, because simple average wind speeds would produce too high annual energy outputs. Weibull distribution is used in probability functions to get more realistic outcomes. Weibull distribution has two major parameters, which are the shape parameter k and the scale parameter λ. These parameters are often provided with wind atlas data. For these calculations a set value of two was given to the shape parameter and the scale parameter was calculated for each mean wind speeds using equation 8. These values are commonly used in SWT certification annual energy production calculations. Figure 49 shows how 6 m/s mean wind speed is distributed using Weibull function with these parameters. (Suomen tuuli atlas.)

$$\lambda = \frac{MWS}{\Gamma(1+{}^{1}/_{k})} \qquad \text{EQUATION 8}$$

λ = Scale parameter

MWS = Mean wind speed

Γ = Gamma function

k = Shape parameter

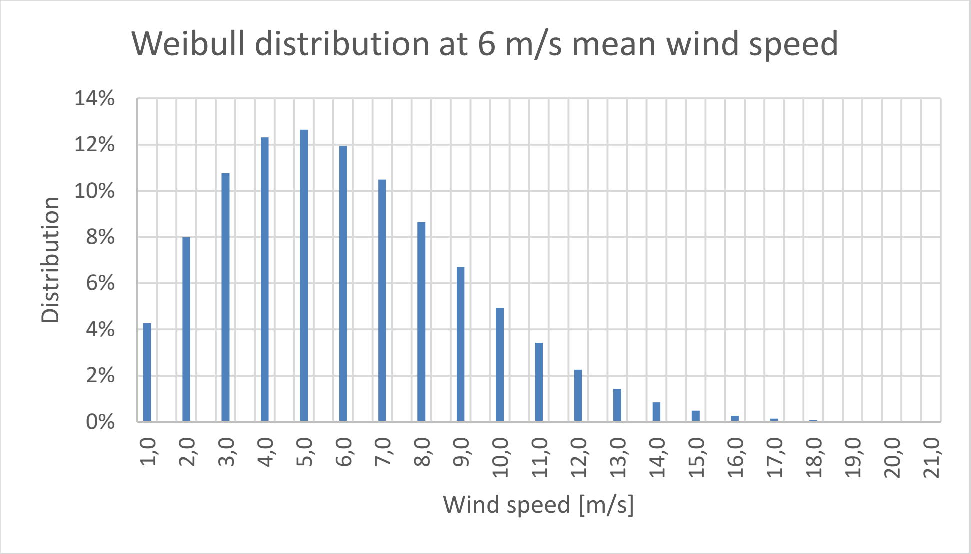


FIGURE 49 Weibull distribution at 6 m/s mean wind speed.

In the economic calculations investment time was set to 20 years, which is a very common life-expectancy for SWTs. The residual and decommission values for the SWTs were counted as zero. This is because their effect on the economic calculations was estimated to be small. Discount percent for the calculations was set to 6%, because it is often used in renewable energy calculations. To simplify the calculations all of the electricity was counted for own usage. The bigger wind turbines might in reality produce more than is used on the property, but a large farm could in theory use all of the production. Cost of electricity was selected as an average value from Finnish consumer electricity prices, which currently is around 13 cents/kWh. Annual price increase for maintenance and electricity was chosen to be 2%, which should be moderate and fair according to recent trends. No deterioration factor was calculated for the energy productions, because regular maintenance was estimated to compensate that. Table 11 has all of the initial values combined together.

TABLE 11 Selected initial values for the economic calculations

Discount rate	6,0 %	
Investment time	20	years
Proportion of own usage	100 %	
Electricity price	0,13	€/kWh
Annual price increase	2,0 %	/year
Decrease in production	0,00 %	/year

In the calculations different economic indicators were compared to multiple mean wind speeds. To give an idea how well the SWTs can perform at different wind conditions. Payback periods were calculated using Equation 3 without any discount factor. Calculated PBPs are plotted using Excel in to graphs, as seen on figure 50. Skystream 3.7 did not produce any annual profit at 4 m/s MWS and therefore no PBP was able to be calculated. All of the SWTs can payback in the 20 year investment time, but at different wind conditions. Out of the chosen SWTs Solid Wind Powers SWP-25 produces the best result and can payback at under 4,5 m/s MWS. A close second is the Endurance E-3120. The Excel 10 pays back in the investment time at over 5 m/s wind conditions. Skystream 3.7 demands the highest wind speeds to pay back in time. The two biggest SWTs reach almost a five year PBP at the highest used MWS.

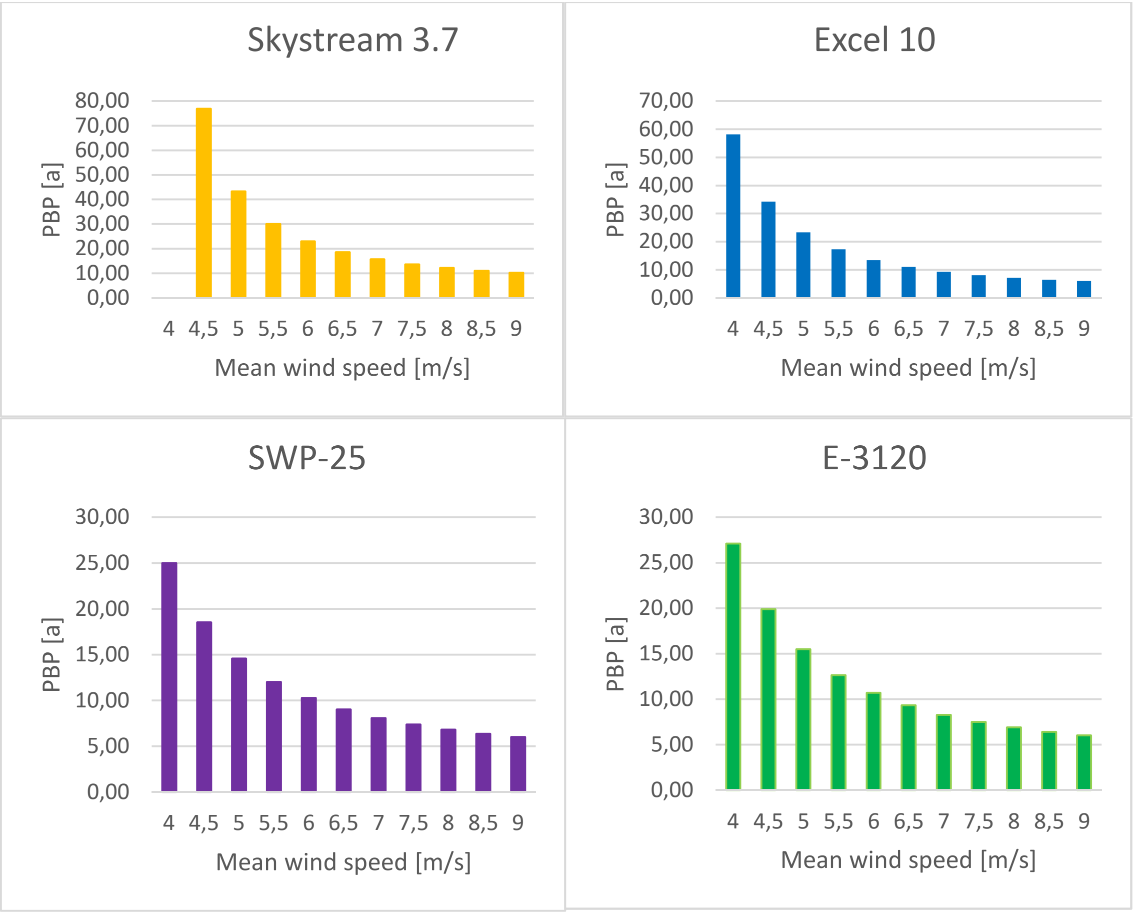


FIGURE 50 Calculated PBPs at different MWSs

Net present values for the SWTs were calculated using Equation 5. NPVs were discounted according to the initial values determent before. Since a positive NPV is an indicator that the project is profitable, all of the SWTs reach it at some MWS, as seen on figure 51. Again the two of the bigger SWTs seems to be more profitable than the smaller. They reach positive NPV between 5,5 to 6 m/s MWSs. The Excel 10 reaches profitability at around 6,3 m/s MWS and the Skystream 3.7 only after 8 m/s MWS. The SWP-25 and the E-3120 produces almost 100 % profit at the highest calculated MWS. As is visible from the graphs in figure 51 all of the SWT produce big losses, at the smallest wind speeds, compared to their initial investment.

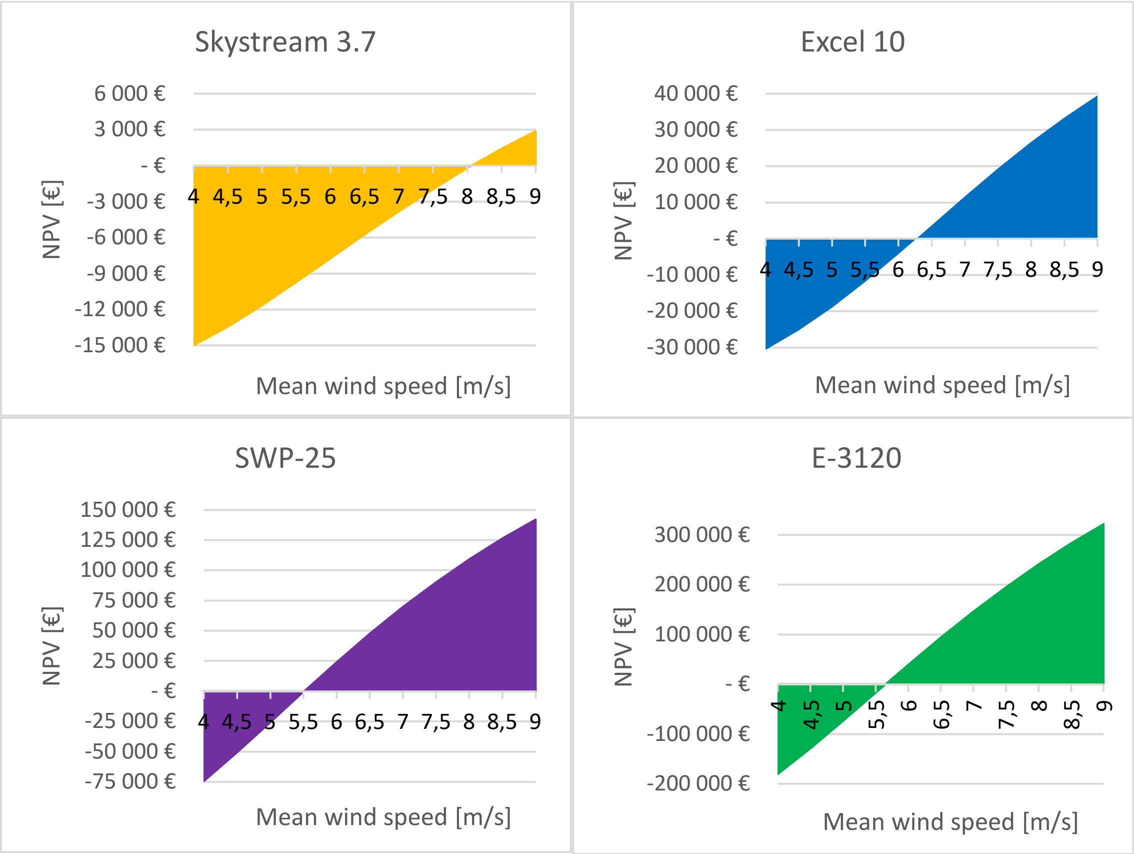


FIGURE 51 Calculated NPSs at different MWSs

Levelized cost of electricity calculations give a good understanding how the SWTs compare against grid electricity. In the calculations only Skystream 3.7 did not reach the Finnish price of grid electricity at any wind speeds. The Excel 10 manages to be cheaper at over 7 m/s MWSs. According to the calculations the SWP-25 and the E-3120 are cheaper than grid electricity at over 6,5 m/s wind speeds. Figure 52 presents the calculated LCOEs at progressive MWSs. In these graphs the dotted red line indicates the Finnish cost of grid electricity to simplify the comparison.

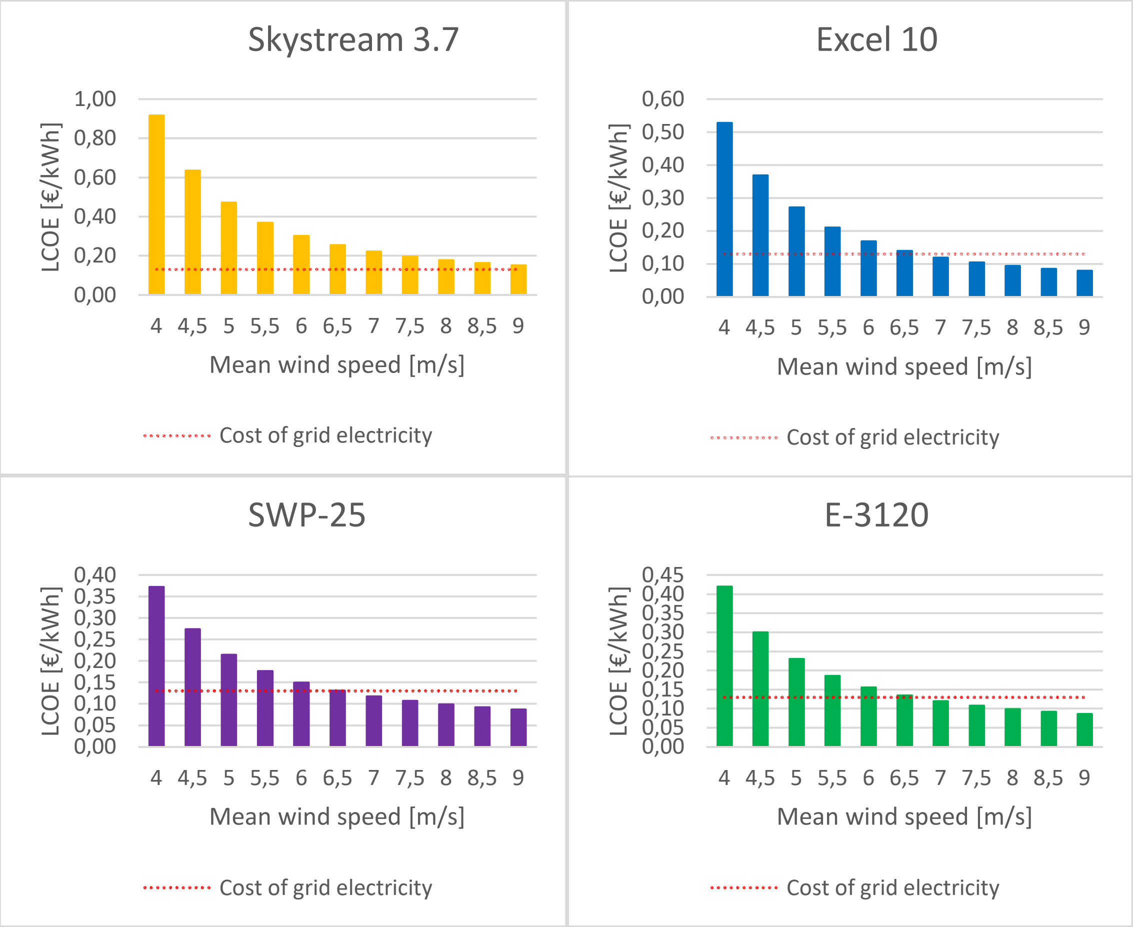


FIGURE 52 Calculated LCOEs at different MWSs

6 CONCLUSIONS

In this thesis the main goal was to figure out if small-scale wind power is currently a viable option for energy production in Arctic areas. The study looks at technological matureness, availability, market status and economic viability. In the technological study chapter HAWTs are compared to VAWTs. The thesis also looks at cold climate impact on SWTs.

Out of the two wind turbine models the HAWT is more advanced and reliable choice. No VAWT has managed to get certification from the leading authorities. It seems that new innovative companies turn up with ground breaking new VAWT design, but they tend to disappear in few years. On the other hand some HAWT companies have stayed in the market for over 10 years. HAWTs are in general more efficient and cheaper than VAWTs.

Arctic areas demand special features for wind turbines in order to function properly. Things like lubricants, rubber seals and other materials need to be cold climate compatible. Also down time due to icing should be considered, when estimating viability in Arctic locations. Some companies do provide special cold climate packages for their products. Arctic features will probably become more readily available when the SWT market matures.

Economic analysis indicates that the smallest SWTs have not reached economic viability. The larger turbines could in theory be viable in many locations in the northern Scandinavia, but not everywhere. Choosing a windy location for the wind turbine is crucial for a profitable investment. Surrounding obstacles can also interfere SWT production and therefore profitability. Prices for SWTs have decreased according to the past market reports and if that trend continues, SWTs could become a good contender in the renewable energy market. Incentives and subsidies from governments could boost the SWT market in Scandinavia like it has done in the UK. It is also good to take into consideration how much CO_2 emissions can be avoided with wind power. Current estimates state that wind power reduces 620–700 g of CO2/kWh (Holttinen et al 2004).

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Xzeres Wind Co. Skystream 3.7

MWS	PBP [a]	NPV [€]	IRR	LCOE [€/kWh]	ROI
4	-	- 14 981,98 €	-	0,9174	-103,32 %
4,5	76,89	- 13 414,45 €	-18,75 %	0,6360	-92,51 %
5	43,32	- 11 634,74 €	-13,13 %	0,4717	-80,24 %
5,5	30,06	- 9 716,72 €	-9,67 %	0,3690	-67,01 %
6	22,94	- 7 734,16 €	-7,04 %	0,3012	-53,34 %
6,5	18,58	- 5 750,59 €	-4,90 %	0,2544	-39,66 %
7	15,68	- 3 815,16 €	-3,08 %	0,2210	-26,31 %
7,5	13,65	- 1 963,15 €	-1,52 %	0,1963	-13,54 %
8	12,17	- 219,06 €	-0,16 %	0,1776	-1,51 %
8,5	11,05	1 399,98 €	1,02 %	0,1631	9,66 %
9	10,20	2 881,67 €	2,06 %	0,1518	19,87 %

Bergey Windpower Co. Excel 10

MWS	PBP [a]	NPV [€]	IRR	LCOE [€/kWh]	ROI
4	58,13	- 30 656,06 €	-15,94 %	0,5282	-87,59 %
4,5	34,20	- 25 303,58 €	-10,90 %	0,3689	-72,30 %
5	23,31	- 18 991,08 €	-7,20 %	0,2721	-54,26 %
5,5	17,22	- 11 895,17 €	-4,10 %	0,2101	-33,99 %
6	13,46	- 4 253,89 €	-1,36 %	0,1687	-12,15 %
6,5	10,98	3 671,42 €	1,11 %	0,1401	10,49 %
7	9,27	11 623,63 €	3,35 %	0,1197	33,21 %
7,5	8,05	19 366,44 €	5,37 %	0,1049	55,33 %
8	7,15	26 695,16 €	7,19 %	0,0939	76,27 %
8,5	6,49	33 444,49 €	8,80 %	0,0856	95,56 %
9	6,00	39 493,02 €	10,20 %	0,0793	112,84 %

Solid Wind Power A/S SWP25-14TG20					
MWS	PBP [a]	NPV [€]	IRR	LCOE [€/kWh]	ROI
4	25,01	- 74 409,03 €	-7,89 %	0,3727	-58,13 %
4,5	18,53	- 50 527,93 €	-4,87 %	0,2739	-39,47 %
5	14,60	- 25 588,51 €	-2,29 %	0,2145	-19,99 %
5,5	12,05	- 502,60 €	-0,04 %	0,1761	-0,39 %
6	10,28	24 038,45 €	1,95 %	0,1498	18,78 %
6,5	9,02	47 548,25 €	3,72 %	0,1311	37,15 %
7	8,09	69 711,31 €	5,29 %	0,1173	54,46 %
7,5	7,38	90 338,15 €	6,70 %	0,1068	70,58 %
8	6,82	109 319,48 €	7,96 %	0,0987	85,41 %
8,5	6,39	126 589,66 €	9,07 %	0,0923	98,90 %
9	6,04	142 105,06 €	10,05 %	0,0873	111,02 %

Endurance Wind Power E-3120					
MWS	PBP [a]	NPV [€]	IRR	LCOE [€/kWh]	ROI
4	27,12	- 180 561,99 €	-8,68 %	0,4200	-62,26 %
4,5	19,89	- 128 779,69 €	-5,60 %	0,3001	-44,41 %
5	15,50	- 73 513,99 €	-2,96 %	0,2300	-25,35 %
5,5	12,66	- 16 982,20 €	-0,64 %	0,1856	-5,86 %
6	10,72	39 109,29 €	1,41 %	0,1558	13,49 %
6,5	9,33	93 562,29 €	3,26 %	0,1348	32,26 %
7	8,30	145 597,71 €	4,91 %	0,1194	50,21 %
7,5	7,52	194 729,35 €	6,41 %	0,1078	67,15 %
8	6,91	240 641,21 €	7,75 %	0,0988	82,98 %
8,5	6,43	283 097,33 €	8,97 %	0,0917	97,62 %
9	6,04	321 895,04 €	10,05 %	0,0861	111,00 %