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TEKNILLINEN TIEDEKUNTA

The economics of wind power: Onshore vs. offshore technologies

Aleksi Kiiski

PROCESS ENGINEERING
Bachelor’s thesis
March 2020

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Tiivistelmä

Jatkuvasti muuttuvassa maailmassa, missä ilmastoasioista keskustellaan alati enemmän, uusiutuvien energiantuotantomuotojen määrä ja merkittävyys kasvaa tauotta. Yksi tällaisista lupaavista tuotantomuodoista on tuulivoima. Tuulivoiman määrä on lisääntynyt suuresti viimeisten vuosikymmenten aikana teknologian kehittyessä. Myöskin hallinnolliset tekijät, kuten vaatimus uusiutuvien tuotantomuotojen käytöstä, ovat lisänneet tuulivoiman tarpeellisuutta. Tuulivoimaa käyttämällä voidaan välttää esimerkiksi hiilidioksidipäästöjä, jotka vaivaavat useimpia perinteisiä energiantuotantomuotoja. Tuulivoimaa tuotetaan tuuliturbiineilla, jotka ovat yleensä massiivisia laitteita, joiden rakentamiseen käytetään paljon materiaaleja, joista suurin osa on metalleja. Tuuliturbiineilla pyritään muuttamaan osa tuulen sisältämästä liike-energiasta sähköksi. Tuuliturbiinit voivat esiintyä useanlaisissa muodoissa. Yksi suuri jaottelu on maa- ja merituuliturbiinien välillä. Kummallakin tuotantomenetelmällä on omat haasteensa nyt, ja tulevaisuudessa. Ongelmat liittyvät pääasiassa tuuliturbiinien hintaan, sekä tuulen ennalta-arvaamattomuuteen. Tuulen ennalta-arvaamattomuus pakottaa sisällyttämään varalähteitä energiajärjestelmiin, mikä lisää kustannuksia entisestään. Myös sähköntuotantokriteerit kasvavat jatkuvasti, mikä asettaa uusia haasteita tuulivoimalle.

Tämä kandidaatintyö esittelee kirjallisuuskatsauksena tyypillisimmät tuulivoiman tuotantomuodot teknologisesta, taloudellisesta, sekä ympäristöllisestä näkökannasta. Työn tarkoituksena on vertailla eri tuuliturbiinimuotoja keskenään ja selvittää turbiinien vahvuuksia, heikkouksia, sekä taloudellista kannattavuutta. Vertailua suoritetaan myös suhteessa joihinkin eriäviin sähköntuotantomuotoihin tietyistä näkökulmista. Lisäksi arvioidaan, kuinka hyvin tuulivoima kykenee vastaamaan sille asetettuihin vaatimuksiin, niin hinnan kuin suorituskyvynkin kannalta. Työssä esitellään tuuliturbiinien periaatteet, pääosat ja rakenteet. Myöskin tuulivoiman kohtaamiin ongelmiin, rajoituksiin ja tulevaisuuden näkymiin ja kehityksiin perehdytään. Meri- ja maatuuliturbiinien lisäksi turbiinit esitellään niiden akselien ja käyntinopeuden perusteella. Lisäksi joidenkin ainutlaatuisten tuuliturbiinimallien toimintaperiaatteita käsitellään. Tuulivoiman soveltuvuutta erilaisissa ympäristöissä ja ilmastoissa, kuten kaupunkiympäristöissä, kylmissä olosuhteissa ja kuivilla alueilla esitellään ja pohditaan. Tuulivoimaloiden kierrätettävyyttä ja elinkaarta, sekä valmistuksessa syntyviä päästöjä arvioidaan. Työssä esitellään tuulivoimapuistojen käyttämistä vastauksena korkeisiin sähköntuotantovaatimuksiin. Samoin käydään läpi tuulivoiman aiheuttamat positiiviset, sekä negatiiviset ympäristövaikutukset.

Työn loppupäätelmissä määritellään ja arvioidaan tuulivoiman käytettävyyttä työkaluna ilmastopäästöjen vähentämiseksi, potentiaalia nousta merkittäväksi sähköntuotantomuodoksi joka puolella maapalloa, sekä soveltuvuutta eri ympäristöihin. Merituulivoimapuistojen kykyjä suurien saastuttavien tuotantolaitoksien korvaamiseksi, vesialueiden hyödyntämiseksi, sekä positiivisten lisäympäristövaikutuksien aikaansaamiseksi arvioidaan. Lisäksi pohditaan, kuinka tuulivoiman kannattavuutta voitaisiin lisätä suunnittelulla, tuulivoiman laajalla levittämisellä ja kierrätyksen määrän kasvattamisella.

Muita tietoja

ABSTRACT FOR THESIS

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Abstract

In a constantly changing world, where environmental issues are discussed more and more, the share and impact of renewable energy production methods are continuously rising. One such promising production method is wind power. The capacity of wind power has increased tremendously in the past few decades due to technological developments. Administrative factors, like the required use of renewable methods in power production have also contributed to the necessity of wind power. Unlike most of conventional power production methods, usage of wind power avoids the release of a lot of emissions, for example carbon dioxide. Wind power is produced by machines called wind turbines, that are usually massive devices. Construction of wind turbines use a lot of materials, most of which are metals. Wind turbines aim at converting some of the kinetic energy of the wind into electricity. Wind turbines can be found in many different variants. One major division in wind turbines is between onshore and offshore wind turbines. Both production methods pose challenges of their own now, and in the future. Challenges revolve mainly around the price of wind turbines, and the unpredictability of wind. The unpredictability of the wind forces the inclusion of reserve backup power in power systems, which increases the expenses even more. The electricity production criteria are also constantly growing, which puts new challenges on wind power.

This bachelor's thesis presents as a literature review the typical wind power production methods from technological, economical, and environmental perspective. The aim of the thesis is to compare different wind turbine models to each other, and to find out the strengths, weaknesses, and economic profitability of different turbines. Comparison is also done in relation to some differing production methods from specific points of view. The ability of wind power to respond to the demands set on it is also assessed from economic and performance perspectives. The thesis presents the principle, main components and structure of wind turbines. The problems, limitations, and future prospects and developments faced by wind power are introduced. In addition to onshore and offshore wind turbines, the turbines are exhibited by their type of axis and rotational speed. Also, the principle of some of unique wind turbine designs are addressed. The suitability of wind power in different environments and climates, like in urban environment, cold climates and arid areas are presented and considered. Recyclability and life cycle of wind turbines are assessed, alongside the emissions generated in wind turbine manufacturing. The thesis showcases the use of wind farms as an answer to the high requirement demands of electricity. Problems faced by wind power are also presented alongside future prospects. Likewise, the positive and negative environmental impacts of wind power are processed.

In the conclusions of the thesis, the use of wind power as a tool in decreasing emissions to the atmosphere, capabilities in rising to a significant electricity production method all over the globe, and the applicability of wind power in different environments are assessed. The abilities of offshore wind farms in replacing large polluting power plants, utilization of water areas, and the accomplishment of additional positive environmental impacts are evaluated. Also, the possibilities of increasing the profitability of wind power through designing, extensive spreading of wind power, and expansion of recycling are considered.

Additional Information

TABLE OF CONTENTS

1 INTRODUCTION

The use of renewable energy is increasing all over the world, as more and more of the ecological advantage provided by the use of renewable energy is uncovered. Renewable energy systems have seen a drastic decrease in expenses regarding manufacturing, thus becoming more economically viable compared to regular production methods. Wind power is among these renewable methods growing in popularity and capacity. Electricity provided by wind power is practically pollutant free. Naturally, producing the material for a wind turbine and transporting the parts into the location of setup will generate emissions, just like in any other electricity production method. The actual operation of the wind turbine is the part where environmental protection takes place, because wind power evades emitting the most common greenhouse gas, carbon dioxide. In addition, no nitrous oxide or sulfur dioxide emissions are released. (Cullen 2013)

Wind power has not existed as a commercial way of producing electricity for a long time, but its improvements have been quite immersive. Wind power has been in some sort of use by humans for several millenniums, but real wind power development started in the 1970s. Turbine sizes of more than one MW (megawatt) were in commercial production just a couple of decades after the turbine size of 100 kW (kilowatt) was reached, and turbine size of 3 MW was reached just a few years after, and the enlargement of turbines has not stopped to this day. First time wind power was used to generate electricity was in the last years of the 19th century. (Ackermann 2012) The usage of wind power has exploded in the past few decades. For example, the global wind power capacity increased more than twelve times in just ten years, between 1997 and 2007. (European Wind Energy Association 2009)

As wind power technologies are quite new there is still improvement to be made in multiple sectors. A lot of effort needs to be put on finding the most cost-effective material compositions for different parts of the turbine in order to make wind power as competitively viable option in power production as possible. But the materials have to be durable above all else, as the constant tension is among the highest in different types of infrastructure. Material costs make a great part of total costs in wind turbines, as their fuel, the wind, is free. (Ancona & McVeigh 2001) Electricity grid networks nowadays are engineered in such a way that the grid will not go down even if a production facility with vast capacity falls from the grid unpredictably and spontaneously. In order to withstand such a loss, the grid must have backup resources at its disposal. The introduction of more and more vast capacities of wind power will bring new challenges to such cases, as wind power brings its own variables and insecurities. The forecasting of wind power must improve to make wind power a more reliable source. (Mur & Bayod 2010, Matos & Bessa 2009)

2 TECHNOLOGICAL OVERVIEW

Wind power technologies can be divided into multiple categories based on different premises. The purpose of this chapter is to describe wind power overall, differences and similarities between common technologies, and their popularity.

2.1 Wind power and wind turbines

The basic principality of wind power is to convert kinetic energy provided by the wind, into electrical energy with help of a generator, but before this can be done, the kinetic energy needs to be transformed to rotational energy. In order to achieve this, multiple components have to be put together in addition to the generator. This combination of technical equipment is generally known as a wind turbine. The most noticeable part of the wind turbine is the rotor. All though there are many wind turbine variations, the most commonly used and the most easily recognizable variation of wind turbine has a rotor formed by several blades, which then are connected to a hub, these two parts together make the rotor. The purpose of the blades is to harness the kinetic energy from the wind, this energy is then transformed to rotational energy by the hub and another component, the gearbox. The gearbox also forwards the rotational energy to the generator. The gearbox and the generator are both located inside a shell called a nacelle. A brake is located inside the nacelle as well, this brake is connected to the gearbox and its purpose is to halt the rotor from achieving dangerous speeds. The nacelle is connected to the tower, which mounts the turbine to ground. Usually the tower weights more than half of the entire turbine, as it supports both the nacelle, and the rotor. The tower, nacelle and rotor together establish the external aspect of a wind turbine. There are numerous other components in a wind turbine, such as coolers and bearings. (Ancona & McVeigh 2001) Up-to-date wind turbines are fitted with various weather detection and measuring devices, such as anemometers and weather wanes to optimize the wind turbine’s rotor according to the wind. Aircraft warning lights are also found on wind turbines nowadays to prevent collisions with aircraft. (Chen & Blaabjerg 2009)

Nowadays wind turbines are required to be able to respond to frequency changes and drops when operating in power grid, so it is not enough if the wind turbines just produce electricity, they need to strictly control how much electricity they produce and at what times. The frequency demands are set by the grid, and in European countries the required frequency is 50 hertz. If there is a slight drop or increase, the power system must respond, either increasing or lowering electricity output into the grid. (Blaabjerg & Ma 2013)

Wind power uses only wind as its fuel, leading to no greenhouse gas emissions in production. This reason combined with comparably cheap expenses in relation to other renewable energy production methods, give good reasons for ever so increasing global wind power capacity. (Lalor et al. 2005) And as wind is available all around the globe, wind power excels at local power production, meaning that transmission distances can be shortened. This also means that wind turbines can be installed at isolated locations, for example on an island that is not connected to the main grid, to increase electricity dispatch in those locations. The price of wind power is not affected by global reserves, unlike oil for example, thus price of wind power can be assumed to remain stable. Wind power is a potent, perhaps even the best, tool that humans have in their disposal at preventing global warming from taking place. Wind power is not able to provide only environmental benefits, but also societal and financial ones. (Saidur et al. 2011) Wind itself is not controlled by humans, but by natural forces, making it a non-dispatchable energy source, this means that wind can be unpredictable and unreliable. But modern designs have given wind power the ability to adapt to current demands on the power grid. Wind power can survive through voltage drops, maintain the frequency, and help with ramp rate when operating in grid. (Mur & Bayod 2010)

There is also a legislative driver for wind power use in European countries, at least in European Union member states, because a required target is set by the European Union in which member states must produce a fifth of their energy by renewable energy sources by 2020. Of course this target can be achieved without using wind power at all because there are many other renewable energy sources besides wind, like solar and biomass, but the use of at least some wind power is going to be needed in most member states if these kind of results are to be achieved. In electricity producing terms, this means that even more than a third of electricity must be produced by renewable methods. Same kind of trend is observable in some states in the United States of America, but the amount of wind power in production methods is lacking behind Europe. (Mur & Bayod 2010)

2.1.1 Betz’s limit

As wind turbines harness the kinetic energy of the wind, converting it to rotational energy, the converted energy naturally causes a reduction in the speed of the wind. If wind turbines were able to convert all of the kinetic energy to rotational energy, it would lead to a complete stop of air flow, and eventually to the stop of operation for the wind turbines, as air would be packed behind the turbines and between the rotor blades. This puts limitations on the operation of wind turbines. This limitation was uncovered by Albert Betz in 1926, and it is known as Betz’s limit. Betz’s limit states that only maximum of 16/27, or roughly 59% of the kinetic energy of the wind can be harnessed. Enabling of Betz’s limit allows wind turbines to keep continuously converting kinetic energy of the wind. (Ackermann 2012)

2.2 Axis of the turbine

One way to characterize wind turbines is by the type of their axis. If the axis is horizontal, then the wind turbine is a horizontal-axis wind turbine (HAWT), and if the axis is vertical, then the wind turbine is a vertical-axis wind turbine (VAWT). HAWTs are the more generic type wind turbine, as they provide better performance, making them a more economic option, and thus a better candidate for power production. All large-scale wind turbines are HAWTs. Their vertical-axis counterparts do have their advantages: they do not need to turn according to the direction of the wind, unlike HAWTs. This makes VAWTs a viable option for future local power production, as they can be fit into urban areas easily. (Badurek 2015) Even though HAWTs are dominating in wind power production, it does not mean that they are superior in every situation and circumstance. HAWTs require stable and high standards of wind to operate properly, otherwise they will start to face problems. Fast and frequent changes in the direction of wind can naturally cause problems for HAWTs, as they need to turn according to the direction of wind, but in addition to that, alteration in the speed of wind causes its own problems as well, as the HAWT needs to adjust to speed also. Turbulence in the wind causes trouble for HAWTs too. All these issues can be avoided by using VAWTs. Specific VAWT systems can operate in varying wind circumstances, added to the fact that VAWTs need much less space to operate, make the VAWT a great candidate for urban wind power production, as they can function in tight environments close to one another and because buildings tend to refract the wind and modify its attributes. (Pope et al. 2010)

2.2.1 Darrieus turbine

One such specific case of a VAWT is the Darrieus wind turbine. The Darrieus turbine was fabricated and patented in the United States by a man carrying the same name. This unique turbine type features two blades that are curved in a way that they resemble jumping ropes that are attached to a vertical axis. The Darrieus turbine has some interesting and distinguishable properties thanks to its unique design. The blades can be made surprisingly light in mass, this means that there is less material used when compared to conventional wind turbines, and this naturally means that material expenditures can be cut dramatically. Unlike in conventional, and most popular, HAWTs where the generator and other equipment are attached to the axis which resides high above the ground, the Darrieus turbine makes it possible that these equipment can be found on the ground level. This leads to easier, and therefore cheaper, maintenance of these equipment. The construction phase is simplified in the process as well. The Darrieus turbine is unable to start itself in normal wind conditions, meaning that after it is stopped by an outside force or it stops due to lack of proper wind, the turbine requires an outside factor to get it into operation again, even with wind speeds that are able to maintain the turbine in operation. Surprising wind blasts are able to start the turbine in some cases, but the starting is unpredictable and unreliable. The starting of the turbine can be achieved with an induction motor that can be also used to supply power to the grid, so essentially there are no extra costs due to this feature because power needs to be fed into the grid in some way or another to make the turbine achieve its purpose. The effectiveness of the Darrieus turbine is comparable to a conventional HAWT. (Johnson 2006)

2.2.2 Savonius turbine

Another unique VAWT type is the Savonius wind turbine. The Savonius turbine was generated in Finland by a man with the same name. The basic principle of the Savonius turbine features barrel-like compartments which have been split and the halves have been deviated from one another to harness the wind. Hence these barrel-like compartments function as the rotor and blades of the turbine. The Savonius turbine is a very amateur friendly design as alternative materials can be used to create the rotors.

The simple design is one of the main benefits of the Savonius turbine. With careful engineering and manufacturing, the Savonius turbine can reach efficiencies that are close to conventional wind turbines. The Savonius turbine cannot maintain reliable frequency for long enough time to be a considerable option to be used in grid. Thus, the Savonius turbine can only be used to support the operation of specific appliances, mainly pumps of different kind. Another downside of the Savonius turbine is the inability to endure winds with high speed, the rotor simply cannot take strong winds. This matter might be solvable with more dedicated research. (Johnson 2006)

2.2.3 Madaras rotor

A unique VAWT design that bases its function on the Magnus effect is known as the Madaras rotor. The Madaras rotor uses a cylinder that is established on a carriage that moves along railroad tracks. The cylinder catches wind and causes the carriage to move because of lift and drag forces. Generators are attached to the wheels of the carriage, and thus electricity could be generated. This design faces several problems with losses and certainty. (Johnson 2006)

2.3 Fixed-speed and variable-speed

Another way to categorize wind turbines is by their way of operation speed. If the wind turbine is operated with fixed speed, the wind turbine's rotors maintain their rotational speed at a constant, no matter how much the speed of wind would increase. The rotational speed of the rotors is kept at the same level to let the wind turbine's generator feed electricity into the grid with same frequency all the time. This means that the gearbox is fixed to operate at a constant state also. Fixed-speed wind turbines have straightforward mechanics when compared to variable-speed turbines, making them easier to operate. Simpler design leads to lower production costs as well. Fixed-speed turbines are also sturdy by their design and people have experimented with more with them than with variable-speed turbines. These issues combined show why fixed-speed turbines dominated the early use of wind power. Just like every other system, the fixed-speed wind turbine comes with its shortcomings. Most notable one of these shortcomings is the inability to react to increase in wind speed results in different parts of the turbine taking the hit as the rotors must be kept from speeding up. This leads to increased tension in many parts of the turbine, this makes the sturdy design more of a necessity than an added benefit. As the name implies, fixed-speed turbines are at their best in one condition set by specific wind speed, this results in great loss of potentially produced electricity. As it is nearly impossible for the wind speed to remain constant in practice, it is expected that the generator cannot keep the frequency of electricity very stable, leading to reduced properties of electricity fed into the grid. This puts more stress on grid control. (Ackermann 2012)

Because of increased research in the area of wind power, and the clear problems with fixed-speed wind turbines, an alternative way of operation in form of variable-speed has overtaken fixed-speed turbines in popularity quite recently. As the name implies, variable-speed turbines are made to work in different wind speeds with much greater performance when compared to fixed-speed turbines. This gives the variable-speed turbine an edge right away, as electricity can be generated in multiple alternating circumstances with improved operating efficiency. These abilities are achieved by installing a transformer between the generator and the grid. The transformer possesses the ability to control the speed of the generator. Having the transformer installed prevents the diminishing of properties of electricity fed into the grid. When compared to fixed-speed turbines, there is less tension put on the whole turbine because other parts do not need to absorb the kinetic energy of the wind. In downsides of the variable-speed turbine, the cost of the wind turbine is presumably increased as you need more components installed, and the whole concept becomes more complex. This leads to more experience and precision required in manufacturing and assembly phase. (Ackermann 2012)

2.4 Onshore vs offshore

Another way to differentiate wind power is based on their platform. The name onshore wind power implies to wind turbines that have been built on land and offshore wind power implies to wind turbines that have been built on water. The global trend in wind power has been very favored towards onshore wind power, and just a very small portion of total global wind energy is produced by offshore wind power. Offshore wind power does provide benefits that the onshore power cannot. And of course, offshore has its downsides as well. The first benefit to occur with offshore wind power is related to its location, as offshore wind turbines are built on sea and coastal areas, space is not taken away from other construction projects, as most of human infrastructure is naturally located on land. As wind power tends to require a lot of space per MW, this opens up vast new opportunities in increases of wind power capacity. Wind also blows more steadily, and the speed of wind is generally greater at sea than on land. The more stable nature of the wind leads to less exhaustion and erosion on the wind turbine. Especially the term in which the turbine's generator can be used is significantly increased. (Esteban et al. 2010) And as wind speeds are higher at sea than on land at certain altitude, the turbines tower can be made shorter offshore, resulting in less material usage. Offshore systems can be built to be much larger than onshore ones if wanted, as much bigger wind turbine parts can be transported by ships on sea more easily than on land using trucks because of limitations set by roads. This fact combined with the easiness of acquiring space for offshore systems, leads to a case where offshore turbines can be constructed closer to higher electricity consumption areas, like cities and towns, resulting in lesser need for transmissions lines and thus, overall transmission distance. (Bilgili et al. 2011)

There are numerous problems with offshore wind turbines when compared to onshore ones, as a system that is going to be built on sea is always going to have some extra costs in construction, operation and maintenance. Some of the disadvantages are straightly related to the benefit provided by the same issue. For example, even though shorter transmission cables are probably required in transmitting the electricity produced by an offshore wind turbine to its user, the transmission lines need to be built from scrap, as practically all of existing grid infrastructure is located on land, and not at sea. As offshore wind is still a relatively new concept in modern energy production, even the designs of offshore wind turbines face problems, especially in the case of the turbine's generator. Due to less tension generated by the wind at sea, the lifetime of generators can be expected to increase, but the maritime surrounding will bring other problems in form of corrosion, and the more stable but significantly higher wind speeds oblige the generators to be more withstanding to other types of forces than just tension. (Esteban et al. 2010) Distinctive ships, personnel and gear are required for offshore wind turbine construction and upkeep, resulting in more costs when compared to construction and upkeep of onshore turbines. Even if the potential space is much more prominent offshore just because it is not occupied by any other piece of infrastructure, there are still quite a lot of limitations on where offshore turbines can be built. The location of construction should not be preferably located too far from the coastline to minimize the need for new transmission cables installed in the bottom of the sea, and to minimize the transmission distance. The ideal distance from coast is about 10 kilometers. The depth of water is another limiting factor if fixed offshore turbines are being built, the optimal depth depends on the type and size of the turbine. The sea floor also causes its own limitations, as it must be sturdy and stable enough in order to provide the wind turbine with enough backing for it to remain operational and standing. (Bilgili et al. 2011)

The ways in which an offshore wind turbine can be attached to the sea floor are numerous. The selection of attachment method is based mostly on the depth of water, one other factor in selection is the popularity of different methods, as the more a method is used, the more knowledge and experience people have on it, making the most used systems the most certain one. The shallower the water, the easier is the use of fixed-bottom methods, and wise versa, when water gets deeper, floating system become more viable. The most used method is called a monopile, basically it is just an extension of the wind turbine's tower that is burrowed into the sea floor. Gravity-based methods rely on gravity to hold the wind turbine at its place, a weight sturdy and heavy enough is based on the sea floor that anchors the turbine. Other methods include different jackets, tripods and floating systems. (Kaldellis et al. 2016)

2.4.1 Popularity

The difference in popularity between onshore and offshore wind turbines is massive, just a couple percentages of global wind power output comes from offshore wind turbines. And the usage of offshore wind turbines is quite location limited when compared to its onshore counterpart, as more than 90 percent of offshore capacity is located in Europe. The fact that total offshore wind power capacity in China, even with its vast population and area, is behind four European countries is extremely surprising. These four European countries even include Denmark and Belgium, which are relatively tiny when compared to China. Even Japan, which is an island nation, does not even remotely rival the top European countries in offshore capacity. The United Kingdom on its own has slightly more than half of the entire global offshore capacity, which is about 8.8 gigawatts. The monopile attachment method is the most popular for offshore wind turbines, approximately only one in five turbines has a different attachment method than monopile. (Kaldellis et al. 2016)

2.5 Site preparation

Before you can be even near erecting wind turbines several steps must be taken. To begin with, land where wind turbines can be constructed must be obtained. Or water if you are talking about offshore wind power. Roads must be constructed on the piece of land in order to make construction and operation of wind turbines possible. At first, these roads will be used to transport the materials needed for wind turbines, and later they will be used for maintenance purposes. And of course, as wind turbines are supposed to generate power they need to be connected to the grid, to achieve this electrical network needs to be put online in the area of the wind turbines. This is a whole another process in itself, and the network needs to be maintained as well. (Johnson 2006)

2.6 Wind farms

Wind turbines are often constructed in close proximity to one another, these installations are called wind farms. When turbines make up a wind farm, the farm is thought as a single power producing unit, comparing to a conventional power plant in power output, unlike a single wind turbine that would dwarf in comparison in output even to a very small scale power plant. The wind farm is a useful tool for matching the output of several wind turbines to the frequency required by the grid. These requirements have been ever so increasing, for example demanding a faster response time. Wind farm allows wind energy to remain relevant power production source even with these demands. Wind farms can be used to reduce component costs, for example the wind turbines in a wind farm can use a shared power converter. (Chen & Blaabjerg 2009)

Offshore wind power is an optimal choice when considering construction of very large-scale wind farms, as it might be extremely difficult to find suitable land in sufficient amounts to house wind farms that are massive in size. These kind of huge wind farms can also diminish value of scenes on land, this problem is avoided when wind turbines are built offshore. As an added benefit, offshore wind provides more stability so there would be less tension on the turbines. However, wind farms with vast capacities display complexities of their own. (Chen & Blaabjerg 2009)

2.6.1 Wake effect

The loss of wind speed caused by a wind turbine will cause the wind not only to lose some of its energy content, but the wind will become turbulent as well. The turbulences caused by a wind turbine will reduce over time, and the wind will eventually be in a stable state. If the wind affected by a wind turbine reaches another wind turbine before it has recovered back to a stable state, the wind will cause the latter wind turbine to experience more stress and tension. The turbulence caused by wind turbines is called the wake effect. When designing wind farms of different sizes, the recognition of wake effect becomes very important in order to get the best performance possible from the wind turbines. The wake effect can reduce the length of life and production efficiency of the turbines. (González-Longatt et al. 2012) Numerous wake effect assessment methods have been developed in order to maximize the effectiveness of major wind farms (Leung & Yang 2012).

3 ECONOMICS OF WIND POWER

Like all power production methods, operation of wind power has its costs. The costs can be divided into initial capital costs that consists for example of the wind turbine, its installation to the ground and attaching to the grid, and costs that are required for the site development, and variable costs that consists of operation, maintenance, and possible repair costs. Rents, taxes and management costs are also included in variable costs. (Blanco 2009)

There are multiple issues that we need to consider when thinking about the economic viability of wind power. Naturally location plays an important role in determining how often, and how fast the wind blows, thus putting severe constraints on electricity production capabilities. Generally, the more elevated a location is, the more wind is featured there. The tall posture of a wind turbine helps in reaching more windy areas, a hub of a modern wind turbine easily reaches 100 meters in height. People do not control the wind; they can only try to forecast it as precisely as possible. This is why wind is considered a non-dispatchable source of energy, just like solar. Because of these facts proper and accurate forecasting is needed to maximize the use of wind power and to relay information on production possibilities to transmission system operators. (Holttinen et al. 2013) When compared to other renewable electricity production methods by economic means, wind power provides a very potent solution for power generation. Hydropower is the only renewable electricity production option that is more advantageous than wind power, this leaves quite many renewable options to be inferior to wind power in economic terms. (Mur & Bayod 2010, DeCarolis & Keith 2005) The serviceability of wind power as an electricity source increases even more when carbon dioxide taxes are introduced to the power production system (Holttinen & Tuhkanen 2004).

3.1 Costs of wind power

Typically, capital costs of a wind turbine make up for most of the total costs, about three quarters. This has a lot do with the fact that fuel costs play no role in wind power, and as fuel costs make up for quite a lot of the variable costs in a conventional thermal plant, for example a plant that uses natural gas as fuel, the ratios of different costs are fairly different in wind power. Out of the capital costs, easily the biggest share goes to the turbine itself, again around three quarters. Second biggest share of investment goes to grid connection, followed by costs related to foundation. These three areas combined account for more than 90% of the capital costs. Grid connection shows the biggest scale of variety, depending on the country where the installation takes place. (European Wind Energy Association 2009) This happens because in some countries the transmission system operator can take full or at least partial responsibility for connections between the grid and the wind turbine that is going to be connected to the grid, and in some countries this can fall fully on the owner of the turbine. The grid connection costs have seen quite a stiff rise since the old days because wind turbines used to be connected to the distribution grid, opposed to being connected to the transmission grid nowadays, which is more expensive. Grid connection expenses can also be unstable in some countries, if laws revolving around them are not controlled properly. (Blanco 2009)

Weather can cause extra issues with wind power by increasing downtime of the turbines. Weather related issues can be very location specific, for example freezing occurs only in relatively few places with wind power. Freezing is an issue for example in Finland, where freezing on average is responsible for 15 to 25 percent of yearly downtime of operational wind turbines. The percentage has been reported to go even as high as 45. The issue with freezing can be even more troublesome, when considering the fact that a portion of downtime caused by freezing can be categorized under some other reason because wind turbines are monitored remotely. Wind turbines in Finland are also switched off when weather data indicates that the air temperature goes below the working condition temperature set by the wind turbines. Older systems can have significantly lower threshold for shutdown than new systems. Newer system thresholds start around minus 25 degrees Celsius when older system thresholds start typically at minus 15 degrees Celsius. These issues contribute to the overall downtime of the turbine, causing the turbine to lose full-load hours. Surprisingly, bigger portion of Finland’s total wind power output takes place during the colder half of year. On average, 60 percent of total wind power is produced between October and March in Finland. (Turkia & Holttinen 2013)

3.1.1 Onshore wind turbine

Expected cost for a wind turbine in Europe is around 1.2 to 1.3 million euros per MW installed to get the wind turbine in operation condition. Operation and maintenance and other variable costs are not included in this figure. Variable costs are produced throughout the entire lifespan of the turbine, and they are assessed to be from 0.012 to 0.015 euros per kWh (kilowatt-hour) produced. A bit over half of the variable costs come from operation and maintenance, rest consists of rents, assurances and general expenditures. Capital costs need to be added in order to calculate the true cost of a kWh produced by wind power. This value is highly dependent on the wind speed featured in the turbine's location, even doubling the cost from lowest 0.05 to 0.1 euros per kWh produced. The mean is set around 0.07 euros per kWh produced. The mean value has decreased almost by half since the mid-1980s, at the same time wind turbines have become more than ten times bigger in capacity on average. (European Wind Energy Association 2009) The speed of wind available and the steadiness of the wind affect the economics of wind power massively, the ideal situation is to maximize the full load hours of the wind turbine. Loss of full load hours will generate economic losses with a factor that is slightly larger than one. (Blanco 2009)

3.1.2 Offshore wind turbine

Offshore wind turbines have a bit different cost structure than their onshore counterparts. Depth of water and distance from the coast are two factors that are not needed to be taken into account in offshore construction. The best situation for offshore wind turbines is to have shallow water and short distance to the mainland, but at the same time have maximum amount of full load hours. This way expenditures related to foundation work and cables can be minimized. In general, it can be said that offshore wind power is one and a half times more expensive than its onshore equivalent. Wind is more procurable when working offshore, this is why bigger turbines are utilized in offshore projects, and naturally larger turbines come with more vast capital costs. Expected capital costs for an offshore wind turbine in a shallow depth location with short distance to the coast, are around 2.0 to 2.2 million euros per MW installed. Foundation work costs can rise to account for more than 20% of capital costs in offshore projects. (European Wind Energy Association 2009) Even though shallower waters and shorter distances to the mainland decrease the cost of offshore wind turbines, the installation costs of European offshore wind power started to increase after the first couple of years of the twenty-first century. Some of the growth in expenditures is due to development in offshore wind turbines, which lead to greater turbines with more capacity, but some is credited to deepening of installation waters and stretched distances from mainland. (Kaldellis & Apostolou 2018)

3.1.3 Wind farms

Wind farms are a potent way of reducing capital costs of wind turbines. Capital costs become cheaper per wind turbine unit the more there are units. If you have built roads and transmission lines for one turbine, it does not cost nearly as much to build them for the second one, and then for the third one, et cetera. The electricity produced by wind turbines in wind farms is cheaper per unit of electricity than in individual wind turbines. (Johnson 2006) The cost of MWh (megawatt-hour) produced by wind power in the United States can vary considerably whether it is produced in a small wind farm or a major wind farm. Major farms with capacity more than 2000 MW could produce one MWh for less than ten dollars, and in comparison, small wind farms required more than three times more money for the same amount produced. (Mur & Bayod 2010, Hirst & Hild 2004)

3.2 Reserve power costs

Because wind power is a non-dispatchable resource and you cannot rely that there is going to be enough wind available to cover electricity consumption at certain times, additional power sources are required to balance this issue out. This duty falls on reserve power, and naturally it is going to have costs of its own. These costs are not directly related to construction of wind turbines or their operation, but they are still necessary for the overall operation of wind power. The acquisition and operation of reserve power is not a burden for the wind turbine manufacturer. (Mur & Bayod 2010) It has been shown that the needed amount of reserve power is the square of mounted wind power (Mur & Bayod 2010, Parsons et al. 2004). In the United Kingdom, reserve power costs are estimated to be around 1.20 pounds per MWh produced if one fifth of the overall electricity usage is provided by wind power. If the amount provided by wind power is increased to two fifths, then the cost of reserve power would be more than doubled, the estimate would then be 2.80 pounds per MWh produced. (Mur & Bayod 2010, Milborrow 2009)

3.3 Wind assessment methods

Numerous methods for assessing wind resources have been developed. These methods focus on different perspectives of the wind, such as consistency of wind speed in an area, frequency of wind, and turbulences in the wind. Thus, the methods give different results on where wind turbines are the most cost-effective. Combination of different methods can provide the best choice for wind turbine site, opposed to just using one. The field of aerodynamics is especially utilized in wind power productivity methods. Even if a location seems theoretically good and productive for wind power, using assessment methods can reveal surprising facts, especially when comparing onshore and offshore locations. Different locations that seem to provide approximate the same amount and same quality wind, can actually differ by dozens of percentages in energy production when assessed properly. (Herbert et al. 2007)

Actual wind turbines are large, and they are complex to mount, thus requiring specialized equipment, personnel and capital, the amount of capital especially increases when talking about wind farms. This is why computer-based assessment and simulation is a useful tool in developing wind power. There are numerous aspects in wind power that require simulation and improvements, like individual components and wind farm templates. (Leung & Yang 2012)

3.3.1 Wind forecasting

Wind forecasting is used to foretell amount of wind in specific locations. This information can be used in predicting how much wind energy will be available for electricity production means, this information can then be used in electricity markets in turn. Wind forecasting is based on meteorological information. (Mur & Bayod 2010) The reliability of wind forecasting must be increased, and the irregularity decreased in order to make wind power a prolonged option for power generation (Mur & Bayod 2010, Boyle 2009). Forecasting methods are primarily used to make sure that hourly electricity production and hourly electricity requirements meet one another as closely as possible. This task becomes increasingly difficult because the consumption is constantly changing, and other production methods can fluctuate as well, due to equipment breakage for example. What makes the matter even worse is that these events can take place very swiftly and unexpectedly. (Mur & Bayod 2010)

3.3.2 Load forecasting

In addition to the wind, the electricity consumption, the load, can and should be forecasted. Forecasting of the electricity consumption has been done for longer than wind forecasting, therefore more experience and knowledge is available on the subject, leading to more precise forecasting. It has been typical that humans try only to predict the load and then match it with production, rather than trying to control or limit the consumption. (Mur & Bayod 2010) Surprisingly, electricity consumption and wind energy availability encase attributes that are reminiscent to one another quite a lot, because unsteadiness and variation are common to both of them (Mur & Bayod 2010, Apt 2007).

3.3.3 Global spread of wind

As wind is location based, the forecasting methods that are used effectively in some areas, naturally might not work in some other areas. The type of wind, meaning its speed, the amount of wind available, its turbulence etc. can be relatively the same in quite a large area, meaning that in some cases same forecasting methods and principles can be used widely. (Mur & Bayod 2010)

4 ENVIRONMENTAL IMPACTS OF WIND POWER

This chapter focuses on environmental issues caused by wind power, as all power production methods cause these issues, some more than others. Life cycle assessment of wind turbines is going to be addressed as well. In the case of wind power, it can be said that environmental impacts are quite diminished. As wind energy does not pollute air with greenhouse gases, and no combustion of any kind is featured, but no electricity production method is without emissions, as production and transportation of construction materials always cause emissions. The effects caused on the environment by wind power are going to be addressed, whether positive or negative. But because these negative effects appear only in slight amounts, wind power is considered to be renewable energy source. Wind power is a very potent candidate in replacing ordinary power production methods, and as wind power is available in usable quantities almost everywhere, it is perfectly suitable for local power production. (Saidur et al. 2011)

4.1 Positive environmental impacts

A wind turbine can negate the harmful effects caused by production and transportation of materials by providing electricity that is free of greenhouse gas emissions, in a relatively short time. The most significant ones of these greenhouse gases are carbon dioxide, nitrogen oxide and sulphur dioxide, because these gases are the main contributors in global warming. Even a very small wind turbine, around a couple of kW in size, can prevent multiple tonnes of carbon dioxide emissions from taking place annually. One MWh of electricity produced by wind power reduces carbon dioxide emissions by around half a ton, when compared with conventional methods that use fossil fuels. The emissions caused by production of materials for a wind turbine are relatively low when compared to ordinary systems. (Saidur et al. 2011) When considering the carbon emissions caused by the production of materials required by a wind turbine and combining them with rest of emission sources, wind power still produces only about ten grams of carbon dioxide per kWh produced (Holttinen & Tuhkanen 2004, Lenzen & Munksgaard 2002).

Wind turbines use very small amounts of water per kWh produced, practically nothing when compared to conventional systems, like coal or oil. The amount of water saved is especially high when compared with nuclear power, wind power does not use even a one-hundredth of the amount nuclear power uses per kWh. The water requirement is manifold even by solar power systems when compared with wind. The saved water can be directed to other areas of need, this is becoming increasingly important day by day, as clean water is vital for humans and total population keeps on growing and living standards get higher. (Saidur et al. 2011)

4.2 Negative environmental impacts

Wind power is able to generate negative effects for both humans and wildlife, the negative effects that affect humans are combination of societal and environmental, and not just environmental unlike for animals. Flying animals like birds and bats are able to fly directly into the rotors of a wind turbine, resulting in fatalities. But these fatalities are dwarfed by many other reasons, such as cats and even power lines that are needed to connect the wind turbines and every electricity production plant to the grid. Large wind turbines naturally require building space as they cannot be built on top of buildings, thus wind turbines can occupy living space from multiple animals. This is true for every power production method that is not building integrated. (Saidur et al. 2011) When it comes to fatalities of animals caused by wind power, numerous issues affect the rates. The type of wind turbine used, spacing between wind turbines in the area, and the characteristics of the wind farm area are all important coefficients. It makes a significant difference in bird fatalities whether the turbines are located on flat and open ground, or in hilly terrain, on top of and between hills. Situational weather plays a key role in circumstances as well, strong winds can direct flying birds and bats towards wind turbines, and rain can affect the senses of animals. (Wang & Wang 2015)

Wind turbines generate unwanted noise when they operate, and because wind turbines require a lot of space to operate, the noise spreads to a large area when wind farms are the production method. The generated noise affects humans and animals alike, and noise is an example of an environmental impact that is felt by humans also. In addition to the noise produced by wind hitting the rotor blades outside the turbine, different components inside the wind turbine are able to generate noise when in operation as well. The noise produced by wind turbines can be a further contributing factor to wildlife fatalities, as specific bats can be lured in by noises with designated frequencies originated from a wind turbine. (Wang & Wang 2015)

4.3 Life cycle assessment

Wind turbines are large machines that require a lot of material for their components, and their foundation works. Life cycle of a wind farm consisting of 11 wind turbines with capacity of 660 kW each was assessed. Each turbine had a total mass of bit under 80 000 kilograms and considering that 660 kW wind turbine is relatively small, a lot of materials are going to be needed for larger, standard size machines. Bulk of the material consisted of steel, around 84 percent. Addition of cast iron and copper increases the amount of metals in total mass to 93 percent. Over 100 kilograms of lubricant oils and almost 5000 kilograms of glass fibre and epoxy resin mixture were found. Construction phase of the wind farm increases the total material usage tremendously, as foundations, roads and many other subjects require vast quantities of rubble, concrete, sand and additional steel. For example, the total amount of concrete exceeded over 4 million kilograms, and the amount of steel used in foundations for the whole farm was about twice the amount used in a single wind turbine. A bit over 90 percent of energy requirements of the wind farm were allocated to production and installation of components. Rest of the required energy went to operation and maintenance, and dismantling. An assumption was made that only a tenth of metals would not be recycled and only a fifth of materials used in the blades would be reused. (Ardente et al. 2008)

5 FUTURE OF WIND POWER

Wind power has vast potential for development, especially offshore wind power. Developments can be improvements in the technology used or decreases in the economic costs of wind power. This chapter focuses on expanding future issues of wind power.

5.1 Component development

Materials that are going to be used in wind turbine components are evolving all the time. Components are aimed to be much lighter in weight, and therefore, cheaper. Especially the tower is in dire need of such an improvement since it alone weights for more than half of the wind turbine in most cases, and the tower can account for even a quarter of the total wind turbine cost. But in order to be able to cut the weight of the tower, the weight that the tower is holding up needs to be cut as well. The rotor of the wind turbine accounts usually for a tenth of the weight of the turbine, and it is alone the single most costly component, even up to a third of the wind turbine costs are derived from the rotor. (Ancona & McVeigh 2001) One new optional tower development method is to start using the already in use steel tubular materials in combination with concrete. Concrete would be used to support the tower from the tower base upwards, and the steel tubes would be located higher in the tower. This new design shows promise at withstanding heavier wind turbine parts that are able to give more power output. (Kaldellis & Apostolou 2018) Generators, converters and other equipment related to power conversion could be the target of component developments as well. Generator developments are quite challenging as wind turbines keep on growing, and therefore so must their generators. The generators need some sort of improvements in order to still fit inside the nacelle. One solution could be the adaptation of high temperature superconductor generators to be used in wind turbines. They are tinier and by providing a wider air slot they are more suitable for operations that require resilience, such as wind power generation. (Blaabjerg & Ma 2013)

5.2 Developments of offshore wind power

It is estimated that in the next ten years offshore wind power will grow tremendously in capacity in Europe alone. European Wind Energy Association (EWEA) assumes that offshore wind power will cover for more than one tenth of total European electricity consumption until the end of this decade. And the harnessed power would be only a small portion of the total potential of offshore wind power in Europe, even after the massive developments. There are a number of companies in Europe that are able to push the offshore wind power technology further and further. In the near future, offshore wind power is capable of improving energy security and economic growth in Europe, and at the same time it is very capable of preventing climate change all around the globe, ever so more efficiently. But a number of issues need to improve so these goals can be reached. (Wieczorek et al. 2013)

Two of the important matters that need to improve in order to obtain the targets are specific markets and study programs. These specific queries for offshore wind power technologies need to especially develop, as specialized personnel are required for efficient operation, and expanded markets will decrease the costs of offshore wind turbines, and hence the acceptance and popularity of offshore wind power will increase. A worthy mention for the success of offshore wind power is the expansion of research and development in the sector, regardless of the possible high risks and costs. (Wieczorek et al. 2013)

5.3 Forecasting developments

Wind forecasting methods are expected to develop further and further. These improvements are aimed at easing with the variation of wind power. If the variation of wind could be controlled more easily, the needed reserve power could be cut down, and therefore costs associated to reserve power as well. The reduction could even be closer to a third of the present costs. (Mur & Bayod 2010)

6 SUMMARY AND CONCLUSIONS

In this section, different aspects addressed in the thesis are summarised. Lastly a conclusion and discussion chapter are included, containing personal thoughts on the issues.

6.1 Technology

Wind power means the use of kinetic energy from the wind in conversion to electrical energy by using machines called wind turbines. The wind is the only fuel used in wind power, meaning that no emissions are produced in wind power operation. Wind is location and weather specific, but generally it can be said that wind is available all over the world. These issues make wind power a renewable energy source, but at the same time wind is a non-dispatchable energy source. Wind power is a potent solution in reaching green energy targets set by the European Union and decarbonizing the atmosphere. Wind turbines consist of many parts and wind turbines can be divided into several variants. Every variant has the same basic principle and fundamental parts, the appearance of components can vary. Main parts include some sort of rotor that captures the energy in the wind, generator that transforms the energy into electricity, and a base of support for the turbine, usually in the form of a tower. In standard and mostly used variants there are multiple smaller components located inside a shell-like structure called nacelle. Wind turbines can be categorized into different variants in multiple ways. Orientation of the wind turbine’s axis divides wind turbines into horizontal and vertical-axis wind turbines. Horizontal-axis wind turbines are the most common and widely used thanks to their better efficiency, but vertical-axis ones have their use as well, because of their need for less space, and potential for their use can be found through varying and special designs. The operation speed of wind turbines is another way to compartmentalize them. Wind turbines can operate in a set, locked speed, making them fixed-speed wind turbines, or wind turbines can be set to adjust to wind speed, making them variable-speed wind turbines. Variable-speed turbines are able to generate a lot more electricity, if the wind speed provides such circumstances. Variable-speed turbines have more components requirements, making them more expensive. Mounting location of wind turbine provides one more way to divide wind turbines. Wind turbines that are built on land are called onshore wind turbines, and turbines that are constructed on water are called offshore wind turbines. Onshore wind power is much more common.

Both provide their own benefits about space usage, potential electricity output, easiness of construction and maintenance, and costs. Offshore turbines can be built larger, having more capacity and they don’t take space from other land-based infrastructure or agriculture, but they are more difficult to erect and maintain, leading to more expenses. Offshore turbines feature more issues due to their surrounding substance, water, and the depth of it. Wind turbines can be built in numerous quantities near each other, creating a wind farm. Wind farms can help wind turbines produce electricity at required frequency and lower the overall cost of wind power. Modelling is used and developed to maximize the usability of wind farms.

6.2 Economics

To justify the economic benefit provided by a wind turbine several issues need to be considered. Wind must be available in sufficient amounts for wind turbine operation in an area that is available for wind power use, thus weather and location play an important role. The wind turbine’s manufacturing and operation costs, land costs combined with all other costs need to be on such a level that construction of a wind turbine is economically justified. These costs can be roughly divided into capital and variable costs. Capital costs consist of expenses required to manufacture and install the wind turbine itself. These include grid connection costs and road constructions required to erect the wind turbine. Variable costs house the expenditures required for operating, maintaining and repairing the turbine, the grid and the area where the wind turbine resides. Variable costs also include possible land rents and tax payments. Capital costs take around 75% of whole expenditures, and about 75% of these capital costs are allocated to the manufacturing of the turbine. Two other big capital cost shares are grid connection and foundation works, making up more than 90% of capital costs in combination with the turbine. Grid connection costs vary based on the country. The total costs vary based on the type of turbine used. Onshore wind turbines cost 1.2-1.3 million euros per MW, whereas offshore turbines cost 2.0-2.2 million euros per MW. These differences are explained by increased amount of effort required by offshore foundation works caused by surrounding water and seabed. The costs can increase when distance from the coast or water depth increases. Variable costs for an onshore wind turbine are expected to be 0.012-0.015 euros per kWh of electricity produced by the turbine. Wind farms can be used as a tool in reducing wind power costs, as roads and transmission lines can be shared in additional wind turbine construction. Wind power requires reserve power that can be used as backup in case of lack of wind power for electricity consumption needs. This issue increases the total capital required to sustain operation of wind turbines, as certainty of enough wind cannot be guaranteed. To combat these uncertainties, effort has been put into developing more precise wind assessment methods. These methods can be used to find optimal location for wind turbines with specific capacities. Wind and load forecasting methods can be used to match the electricity production and electricity consumption as closely as possible. Wind forecasting focuses on finding out the wind speed, its turbulences, and how long wind will be available in specific areas.

6.3 Environmental impacts

Production of electricity by wind power is free of emissions, and thus is a potent tool in fighting global warming and carbonization of the atmosphere. Use of wind power reduces the amount of carbon dioxide when compared to conventional combustion methods. Nitrous oxides or sulfur dioxide are neither produced in wind power operation. MWh of electricity produced by wind power is equivalent to 500 kg reduction of carbon dioxide. When including emissions in production of wind turbine materials, around 10 grams of carbon dioxide emissions are produced by kWh produced by wind power. One another environmental benefit that wind power gives effective reduction on the amount of water needed by electricity production. When compared to other methods it can be found that solar power requires multiple times the water per kWh and nuclear power requires more than one hundred times the water per kWh produced. Operation of wind turbines can have a negative effect on both animals and humans. Flying creatures can die due to collision with turbine blades and wind turbines can disturb animals by sound, or just by simply existing on their turf. Humans can be disturbed by the noise generated by turbines and turbines can ruin scenery. Life cycle assessment of a wind farm showed staggering amounts of material required for wind power operation. Even a moderately small wind turbine of 660 kW had a mass of almost 80 000 kg, 84% of it being steel. In addition, materials such as concrete, rubble and steel used in foundations increase the total material requirements tremendously when roads, foundations for the turbines and other side uses are included.

6.4 Future developments

Wind power materials require improvements in shape of becoming lighter, and thus cheaper because materials are not required in such vast quantities anymore. The tower and rotor of a wind turbine are both heavy components, and expensive ones. Towers can possibly be built from combined material consisting of tubular steel and concrete. Generator developments show promise in form of high temperature superconductor generators that can be packed in smaller spaces. Offshore wind power is expected to rise its share in electricity production in Europe in the near future, but for this to happen, a couple of things need to improve. Designated markets for offshore wind power need to be addressed for it to grow to be a competitive option in power production, and training of specialized personnel needs to be ramped up in order to reach effective operation of offshore wind power. Wind forecasting developments aim at reducing the need for reserve power by making wind prediction more accurate and reliable.

6.5 Conclusion and discussion

Wind power has potential of becoming the worlds most used electricity production method, as wind is free, basically unlimited, and available all over the world. Wind is weather and location specific, but by effective prediction and widespread installation of wind turbines, the production of electricity can be guaranteed to a large extent. This can be applied for example on a country, or continental level, meaning that southern part of a country might not have wind in adequate amounts, but its northern parts do. And same thing can happen throughout whole Europe, a northern nation might not have enough wind, but a central European nation has. Most of the materials used in wind turbine construction are found or made in plentiful amounts in numerous locations, as steel and concrete are the two mostly used substances. Manufacturing of these materials naturally generate carbon dioxide emissions, but wind turbines are able to pay back these emissions manifold. The minor need for water by wind power creates possibilities for wind power use in arid areas, and fresh water can be directed to other areas of need than power production. This makes wind power a highly possible candidate in developing countries. Wind power also proves to be a potent electricity production method in colder climates, as winter basically causes only minor pauses in production. Solar power, another green energy solution that can reduce carbon dioxide in the atmosphere, suffers from efficiency loss in wintertime in northern countries, as the sun simply doesn't shine enough. Wind power poses no such difficulties.

The multiple variants of wind turbines give wind power the ability to adapt to different conditions. VAWTs can be constructed in urban environments, on top of buildings for example. This means that power required by cities can be generated there as well, just like building-mounted solar panels. Development and use of offshore wind turbines free space on land for other uses. Island nations and countries with long coastlines have significant potential for power production, as they have large water areas to be utilized. If a foundation method for offshore wind turbines that requires minimal work were to be developed, the cost of offshore wind power would be drastically reduced, as foundation work can count for significant amount of capital costs in offshore wind power. Usage of large-scale offshore wind farms provide capabilities even on replacing large conventional power plants. Offshore wind turbines can be placed more easily in locations where they don't interfere with bird and bat flight paths, as water surface is flat and there are various options for placement locations.

The operation and maintenance costs of wind power are minimal. After the wind turbine has paid itself back through electricity sales, the wind turbine produces almost pure revenue. This would mean that if the manufacturing costs of wind turbines were to be reduced, and/or the lifetime of wind turbines were to be increased, the profitability and therefore use of wind power would increase considerably. These issues could be achieved through careful engineering and research. The throughout spread of wind turbines and better forecasting of wind could diminish the need for reserve power widely, further increasing profitability. Higher recycling of materials, especially metals as they need to be mined, melted and casted, would be an important factor in the future usage of wind power, as manufacturing costs could be brought down with effective reusing.

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