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Innovating the Supply Chain of Wind Energy Through the Application of Additive Manufacturing

Brett C. Kraynyk
Daniel W. Janzen

Supervisor: Aksel Ivar Rokkan

Master Thesis: ENE Profile

NORWEGIAN SCHOOL OF ECONOMICS

Abstract

3D Printing, more commonly known today as Additive Manufacturing, is an industry that is growing at tremendous rates, with a forecasted market size of over $20 Billion USD within the next 3 years. Firms like Ford Motor Company, Boeing, Airbus, Lotus, BAE, Maersk, and General Electric are already using Additive Manufacturing technology in their manufacturing processes, in applications such as creating molds for casting, and rapid prototyping. Additive Manufacturing stands to create numerous benefits over traditional production processes, and as the industry matures, we will see it become more prevalent in various aspects of our lives. When looking to the energy and environmental sector, studies say that an expected 10% of oil & gas companies will have adopted Additive Manufacturing by 2019. However, the wind power sector presents another opportunity, maybe not yet tapped, to utilize this technology to manage their supply chain better, gain better control of production processes, and most importantly, cut costs and speed up time to market with new designs. The question at hand was, "Does Additive Manufacturing have the potential to contribute to lowering the cost of wind energy through aiding innovation in the wind power sector and/or lowering the cost to produce wind energy"? To answer this question, we aimed to determine the feasibility of producing various components of a wind turbine through the Additive Manufacturing process. After careful consideration, it was determined that the greatest opportunity would be to pursue the production of turbine blades. Additive manufacturing provides the opportunity to produce lightweight components, reduce manufacturing lead times, and decrease material wastage in the manufacturing process. The primary aim of this project was to determine a method to reduce overall turbine costs, however, several additional supply chain and logistics benefits were derived along the way. Through extensive cooperation with a variety of industry experts, this study was able to determine that a cost reduction was most feasible by leveraging Additive Manufacturing to produce molds for turbine blades. This would have a significant impact on reducing overall throughput time from design to production, will reduce overall turbine blade costs, and will enable turbine manufacturers to vertically integrate, by either owning processes that were traditionally outsourced, or by removing costly and time-consuming productions steps altogether.

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Lonnie J. Love & Brian K. Post

Drs. Lonnie J. Love & Brian K. Post of the Oak Ridge National Laboratory were essential for this project, and were kind enough to sit through numerous conference calls, and allow us access to their research in Big Area Additive Manufacturing as it relates to wind turbines. Lonnie is the project lead for the Big Area Additive Manufacturing program at ORNL that is focusing on large scale, high-speed polymer and metal additive manufacturing. Brian is an associate research staff member with the Manufacturing Systems Research Group at Oak Ridge National Laboratory. Brian's research includes the development of large-scale additive manufacturing processes capable of producing large parts.

Landon R. White

Landon White is consultant and manager who has spent many years with some of the world's best management consulting firms. He deals with supply chain advisory, but also has a passion for additive manufacturing, and holds a certificate in additive manufacturing from the Society of Manufacturing Engineers. Landon was essential in providing advice throughout the course of this paper, and helped connect us to a variety of industry experts, even flying out to Tokyo with one of the authors to attend a conference to learn about additive manufacturing, and speak to industry innovators about its future in business.

Norwegian School of Economics

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Summary of Technical Terms & Acronyms

AM: Additive Manufacturing

BAAM: Big Area Additive Manufacturing.

Capacity: The maximum power output from an energy production source

CCM: Cubic centimetres

LCOE: Levelized Cost of Electricity, the average cost to produce energy, typically measured in KWh, MWh.

Mold: An inverse representation of the finished product typically produced using a ‘plug’ (see below). The mold is used to produce the finished product.

MWh: Megawatt hours, a measurement of energy (in Megawatts) produced or consumed over a specified time period.

Plug: A physical representation of the desired finished end product, used to produce a mold. Also known as a ‘master mold’.

TW, GW, MW, & KW: Terawatts, Gigawatts, Megawatts, & Kilowatts. Measurements of power by reference of the rate at which it is produced or consumed at a moment in time. 1 Terawatt = 1 000 Gigawatts, 1 Gigawatt = 1 000 Megawatts, 1 Megawatt = 1 000 Kilowatts, 1 Kilowatt = 1 000 Watts

PC: Personal Communication

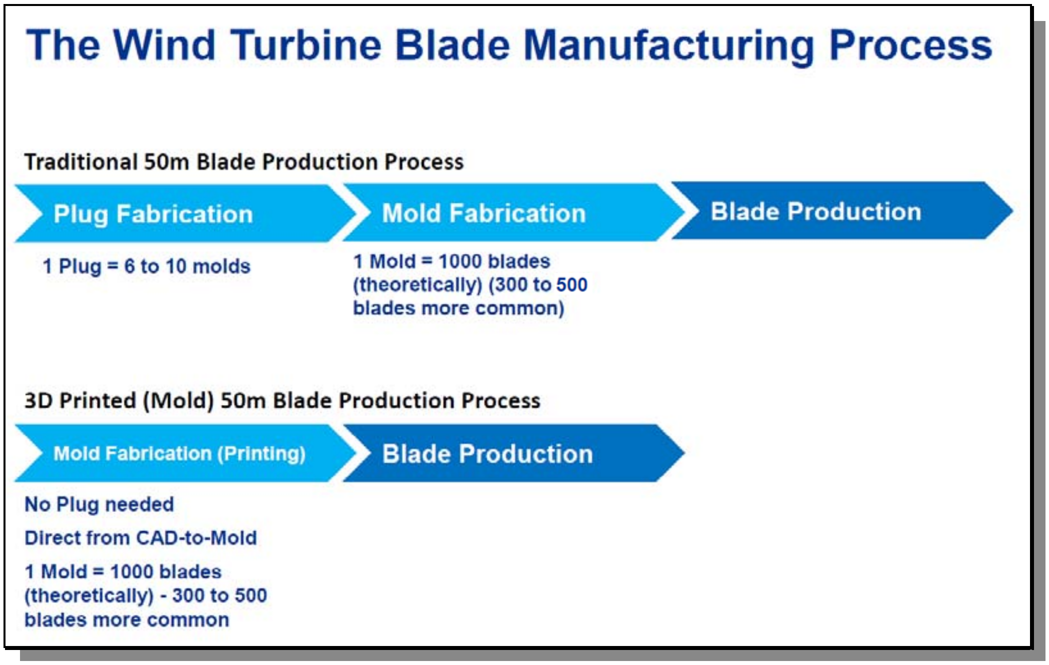
CONTENTS

1. Our Approach: Combining Wind Turbines & Additive Manufacturing

A windmill can be broken down into a variety of components, however, not all of these components have the potential to be manufactured using additive manufacturing techniques. For the purpose of this thesis, we looked thoroughly at all the components in a wind turbine, and solicited a variety of expert opinions as to which parts were the best use of the technology. The blades are the most significant cost component that we found to be feasible to apply additive manufacturing. We chose to look in depth at a 50-meter blade, common to the commercial wind turbine market. We acknowledge that this study would also be feasible for replacement blades, and other issues related to turbine breakdowns or maintenance, however, we would like to focus strictly on the cost savings achievable in new-build construction. While additive manufacturing can be applied in many cases with wind energy, this specific application studies the effect switching between the two types of manufacturing would have specifically related to new wind turbine blades installed on new build wind farm sites.

In this thesis, we first take a look at both the wind energy industry, as well as the additive manufacturing industry to develop a baseline of understanding for the reader. Following these introductions is a literature review covering both wind energy and additive manufacturing to better understand the current research and market sentiment in each respective market. Finally, the thesis goes in depth in comparing blade manufacturing using traditional approach of manufacturing and additive manufacturing.

Other parts were also considered qualitatively in this thesis; however, the concentration of this thesis is the comparison between these two types of manufacturing applied to the blade manufacturing process, specifically the tooling required for blade production. The manufacturing process typically constitutes the construction of a model of the final blade, known as a “plug”, this plug is then used to make a series of molds, which are then utilized to produce final blades. One plug makes an average of 8 molds, each mold is then capable of producing 1000 blades theoretically although amounts of 300 – 500 are more common in reality. A high-level overview of the two processes can be illustrated as follows:



The Wind Turbine Blade Manufacturing Process

Traditional 50m Blade Production Process

Plug Fabrication

Mold Fabrication

Blade Production

1 Plug = 6 to 10 molds

1 Mold = 1000 blades (theoretically) (300 to 500 blades more common)

3D Printed (Mold) 50m Blade Production Process

Mold Fabrication (Printing)

Blade Production

No Plug needed

Direct from CAD-to-Mold

1 Mold = 1000 blades (theoretically) - 300 to 500 blades more common

Figure 1: Conventional Process vs Additive Process, Created by Authors

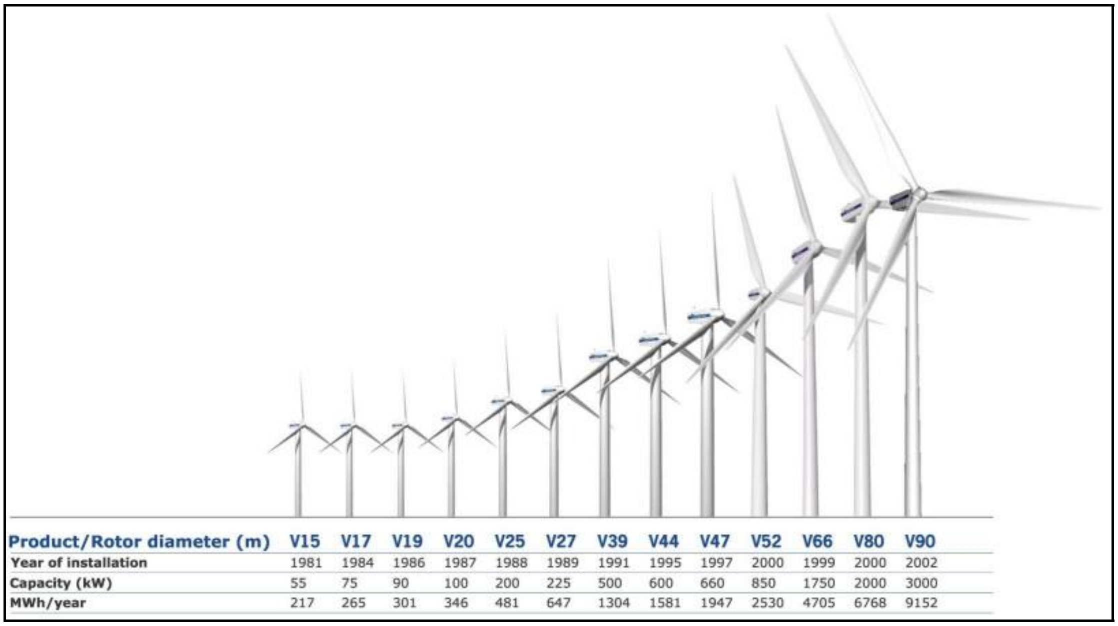
2. Wind Energy

2.1 Introduction

Wind energy has long been utilized by mankind since as early as 5000 BC when it was first used to propel boats along the Nile River. Evidence suggests that the first use of a wind turbine was around 2000 BC in ancient Babylon. By the 10^{th} century AD, upright windmills with ‘blade’ surfaces as long as 5 meters and as high as 9 meters were grinding grain in the middle east. It was not until later in the 12^{th} century that wind power was brought to Europe. By the late 1800’s there was approximately 100 000 windmills operating in Europe primarily for the use of grinding grain or powering pumps (Asmus, 2001).

Modern electricity production was first invented in 1800 by Alessandro Volta and further refined by Michael Faraday, who developed electricity generation (Atkinson, 2015). It did not take long before scientists learned of how to transform wind energy into electrical energy. The first windmill for electricity production was built in 1887 in Glasgow, Scotland by Professor James Blyth (Nixon, 2008).

The modern era of wind power began in 1979 with the mass production of wind turbines by Danish manufacturers including Kuriant, Vestas, Nordtank, and Bonus. In the infancy of this industry, wind turbines often had very low production capacities, somewhere between 10-30 kW. If we look forward to the present, windmills of this type of capacity are now often found in small-scale, or even private wind farms. By 2011, the average size of grid-connected wind turbines was around 1.16 MW (BTM Consult, 2011), while most new projects now use wind turbines between 2-3 MW. Additionally, a typical industrial scale modern wind turbine has a blade sweep of between 80-100 meters compared to the original sizes of approximately 10-15 meters. Figure 2 illustrates the development of wind turbine scale over time.



Product/Rotor diameter (m)	V15	V17	V19	V20	V25	V27	V39	V44	V47	V52	V66	V80	V90
Year of installation	1981	1984	1986	1987	1988	1989	1991	1995	1997	2000	1999	2000	2002
Capacity (kW)	55	75	90	100	200	225	500	600	660	850	1750	2000	3000
MWh/year	217	265	301	346	481	647	1304	1581	1947	2530	4705	6768	9152

Figure 2: Blade & Turbine Size Over Time, Source: Vestas

2.2 Why Wind Power?

Electricity produced by wind energy currently accounts for 2.5% of the global supply of electricity and is the second largest renewable electricity generation source. In 2015, onshore wind lead the renewable energy additions accounting for more than 1/3 of all new renewable energy additions (IEA, 2015). The global average cost of electricity produced by wind is $85 USD as of 2013 with a range of $50 – 440 USD per MWh making it one of the most attractive renewable energy sources and energy sources (Salvatore, 2008). Additionally, as there is no fuel cost associated with wind energy production, it removes the fuel price uncertainty associated with other types of energy production such as coal and gas plants (IEA, 2015). As the world continues to develop and the demand for energy increases, new supplies of energy will be needed. Furthermore, there is growing concern and demand from citizens all over the world to switch toward renewable energies. The aim of our research was to determine if a new manufacturing process, 3D printing, could be utilized in the wind energy industry in order to reduce the cost of wind energy.

2.3 Electricity Production

Electricity is the fastest growing form of end-use energy consumption. Electricity demand has increased by over 50% since 2000 and is expected to grow an additional 60% by 2040 based on current forecasts (Figure 3). Electricity demand, like other forms of energy, is largely tied to GDP, as a significant amount of electricity demand is linked to industrial activity.

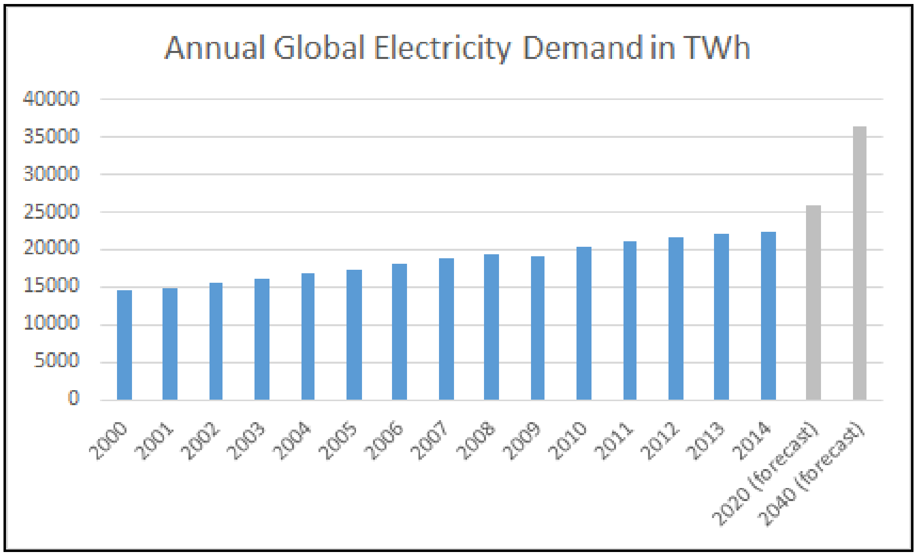


Figure 3: Annual global electricity demand history & forecast, Source: US Energy Information Administration (EIA)

Globally, electricity generation continues to be dominated by burning of fossil fuels, predominantly coal in recent years there has been an increasing number of combined cycle gas plants due to the recently low price of gas and the highly flexible nature of these plants to ramp up or slow down production with short notice.

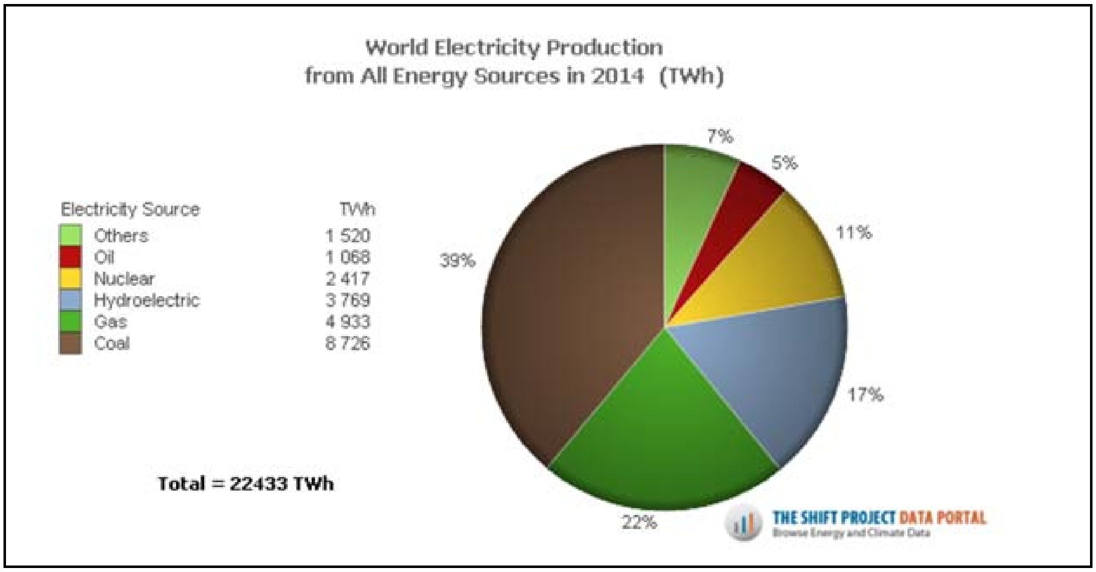


Figure 4: World electricity production by source, Source: World Bank - World Development Indicators

As previously stated, wind makes up 2.5% of total electricity production. In 2015, the installed capacity of wind surpassed 400 000 MW. Figure 5 shows the cumulative installed wind capacity globally over a 15-year period and the forecast for the next 5 years. This highlights the fact that wind has been a fast-growing industry in recent years and expected to continue expanding at the same pace.

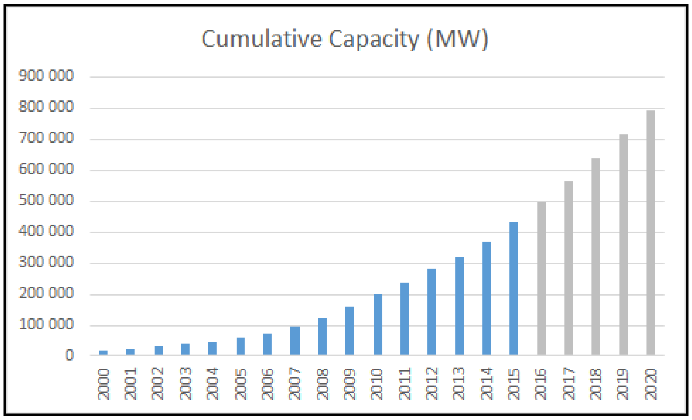
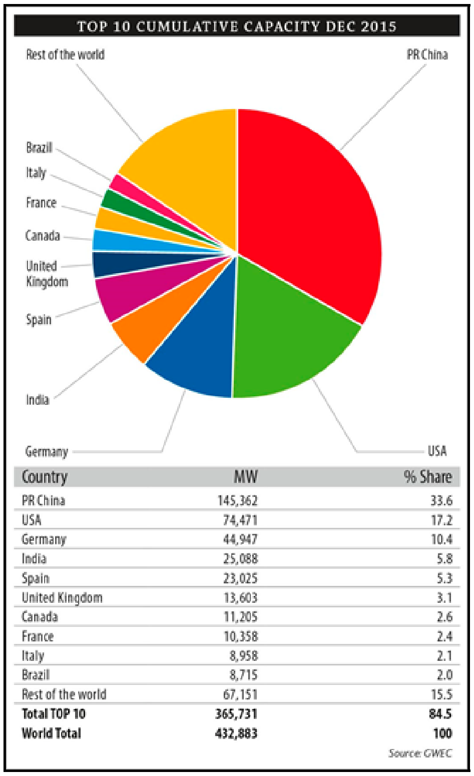


Figure 5: Global cumulative capacity of wind energy, Source: Global Wind Energy Council



Country	MW	% Share
PR China	145,362	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,205	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of the world	67,151	15.5
Total TOP 10	**365,731**	**84.5**
World Total	**432,883**	**100**

Source: GWEC

Figure 6: Installed wind energy capacity by country, Source: Global Wind Energy Council

Together, China and the United States currently make up half of the worlds wind energy capacity (Figure 6). As of Fall 2013, the largest onshore wind turbine farm in the world had a capacity of 1,550 MW is situated in California, USA. The wind farm is comprised of 586 turbines ranging from 1.5 MW to 3 MW in capacity, from turbine manufacturers Vestas & GE (Power Technology, 2013). The largest offshore wind turbine farm in the world was located 20 km off the coast of the UK and has a capacity of 630 MW. The wind farm is comprised of 175 turbines supplied by Siemens, each with a capacity of 3.6 MW. Despite the lack of appearance in the top 10 countries by capacity, Denmark is the world leader in proportion of electricity generation from wind energy. Presently Denmark produces more than 40% of its electricity from wind energy and has goals to reach 50% by 2020 (Government of Denmark, 2015).

2.4 Wind as a Resource

Many studies have been done to identify the global wind resource potential. Estimates vary from ~55 000 GW to ~3 500 000 GW depending on the study and methodology (Hossain, 2014, p. 30). Unfortunately, due to the lack of wind speed and geographical data available globally, there is no precise data. One of the most persuasive studies suggests that placing 2.5 MW turbines with 80m hub heights in all areas that are non-forested, non-urban and ice-free, and have an average capacity factor of 20%, would produce 840 000 TWh. This would result in annual electricity generation 37 times the global electricity production in 2015 (Hossain, 2014, p. 30). No matter which study or methodology is applied, it seems clear that the resource has potential.

2.5 Wind Turbine Technologies

There are many different types of wind turbine technologies in use today. Wind turbine technologies can vary by:

- Axis (vertical or horizontal)
- Rotor placement (upwind or downwind)
- Blade length
- Hub height
- Number of blades
- Output regulation system for the generator
- Hub connection to rotor
- Gearbox design (multi-stage, single stage, or direct drive)

Modern utility scale wind turbines are horizontal axis, with upwind rotor placement, have a blade length of 35 to 56 m long, a hub height of 60 to 105 m, have 3 blades, output of 0.5 MW to 3 MW, and a direct drive gearbox design (IRENA, 2012). There are many technical and economic reasons for these specifications and their variances, however this thesis will not cover these topics. This thesis will focus on wind turbines and wind turbine farms of these characteristics as they dominate the industry.

2.6 How Does a Wind Turbine Work?

A wind turbine works by converting the wind (kinetic energy) into electrical energy. It does this by utilizing the wind energy to turn the blades, which creates mechanical energy. The mechanical energy is then converted into electrical energy using a generator, which is then put into the electrical grid to be consumed.

There are three main factors which affect a wind turbine's output that comprise the wind power formula:

$$\text{Eq 1: Power} = 0.5 \times \text{Swept Area} \times \text{Air Density} \times \text{Velocity}^3$$

- Blade Radius
    - Determined by purchaser and manufacturer
    - Larger blade radius’ generate more power
- Wind Speed
    - Varies by location, time of day & year
    - Higher wind speeds preferable
    - Stable winds preferable
    - Higher altitudes generally have higher, more stable winds
- Air Density
    - Varies by location, time of day & year
    - Function of altitude, temperature and air pressure
    - The denser the air the higher the kinetic energy present

A wind turbine is optimized to produce maximum electricity with average wind speeds. A typical wind turbine starts working at wind speeds of 3-4 meters per second and shuts down at approximately 25 meters per second (depending on turbine design) to protect the wind turbine from damage (figure 7).

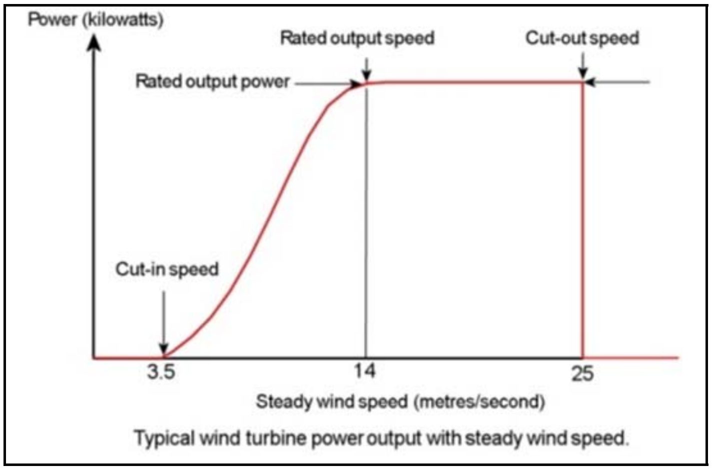


Figure 7: Power curve for wind turbine based on wind speed, Source: UK Wind Speed Database

The output of the wind turbine increases at a cubic rate until the point at which it reaches maximum power output also known as the turbine capacity. This is consistent with the wind power formula. When the turbine reaches maximum power output the blades are angled into the wind such that the power output remains at, but does not exceed generator capacity.

Based on the known wind power formula, it is clear that wind speed is a key factor in determining the amount of power generated from a wind turbine, and therefore controlling the cost of electricity produced per MWh. Furthermore, we know that average wind speeds vary by geographic location, therefore location of the wind turbine is a key factor in controlling the cost of electricity produced per MWh. There are many factors to consider when placing a wind turbine or a collection of wind turbines. Project analysis must weigh the benefits and costs when choosing the location of a wind farm.

Air density has a lesser effect on the power of the wind turbine, because the air pressure variance between areas is not significant, and additionally does not affect the power formula by any factorial as in the case of wind speed.

Swept area is another important variable within the wind power formula. This is because the larger the area the more power the turbine can “catch”. A seemingly negligible 1 meter increase in the blade length results in a significant increase in the swept area.

The formula for the swept area of a turbine: A = pi * r^2 shows that the effect of increased blade length has a multiplicative effect on the swept area and therefore the wind power formula. For example, with a 40m long turbine blade, with sweep area of 5,026 m^2, when blade length is increased by 1 meter to 41 meters would give a resulting increased sweep area of 5,281 m^2, or an increase of 255 m^2.

2.7 The Wind Turbine Market

The utility scale wind turbine market can be best described as an oligopolistic. It is mainly comprised of large market players, where the largest 10 companies control 68% of the market (figure 8). The largest concentration of wind turbine suppliers is in Europe.

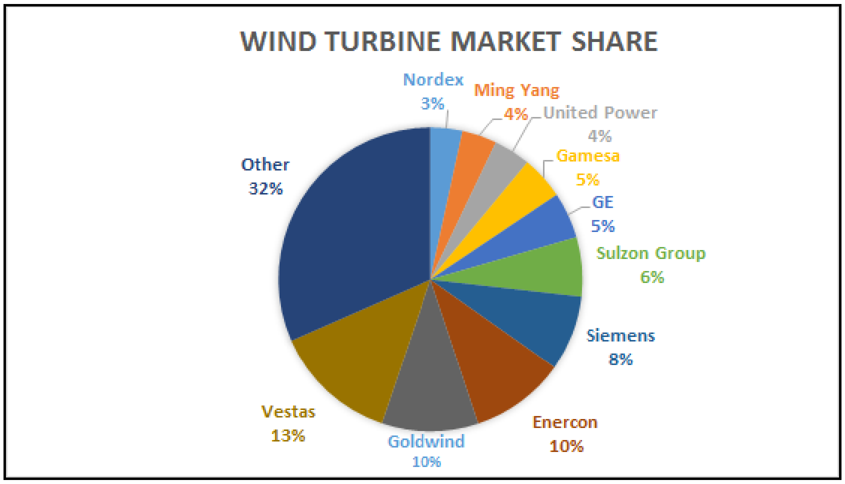


Figure 8: Wind turbine market share by company, Source: Energy Digital Magazine, November 2014

2.8 Benefits of Wind Energy

Communities generally view wind power in a positive light, carrying the opinion that it is a reliable source of clean energy, and support greater implementation of wind farms in their energy generation mix (Stein, 2013). However, studies have also shown that one group of people may not hold these views, which would be those living in very close proximity to a wind farm site (Swofford & Slattery, 2010).

One of the most substantial benefits of wind energy is the low greenhouse gas (GHG) emissions as compared to other energy generation sources. In this area, wind energy is amongst the lowest of all possible generation methods. Below is a comparison of lifecycle emissions from different forms of electricity generation:

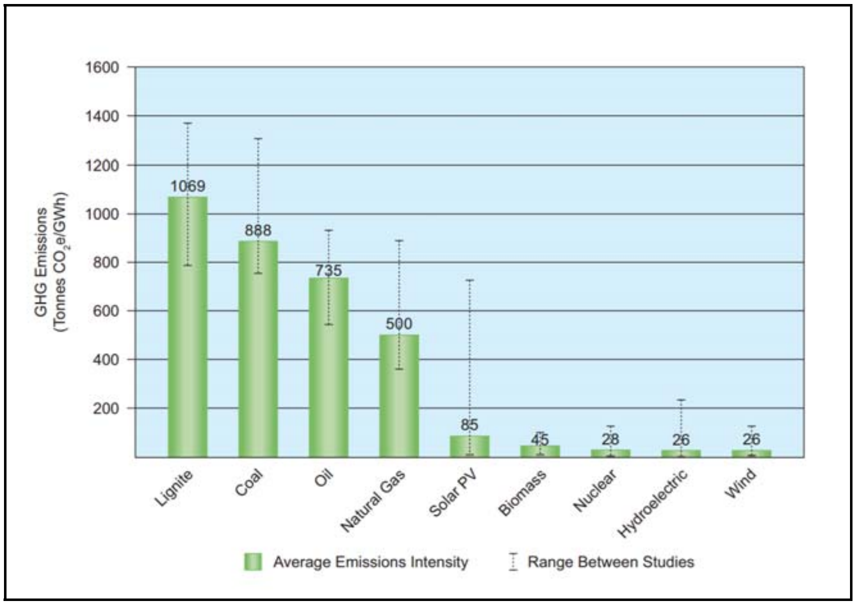


Figure 9: Comparison of greenhouse gas emissions by electricity generation type, Source: World Nuclear Association

Additionally, wind energy has no input fuel required. This mitigates any concerns about energy security, as there is no need to ever import fuels to produce power. Therefore, it can be seen as an effective hedge on the price of electricity production.

One of the most substantial benefits of wind energy, which is the most important focal point of this thesis, is the relatively low Levelized Cost of Energy (LCOE) as compared to other generation sources (Figure 10). LCOE is the utility industry's most commonly used metric in terms of measuring the cost of energy produced by a generator. Wind power has a lower total system LCOE than conventional natural gas, advanced nuclear, biomass, solar PV, and hydroelectric power (US EIA, 2017).

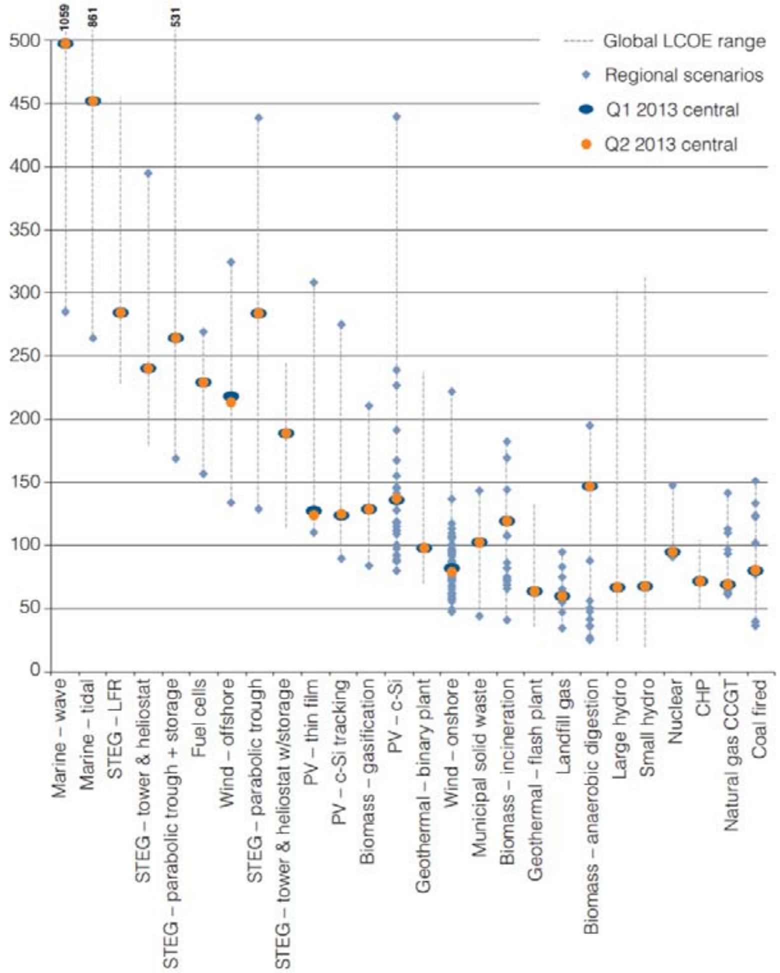


Figure 10: Comparison of electricity production LCOE's by generation type, Source: World Energy Council, 2013

2.9 Disadvantages of Wind Energy

Thus far, we have focused heavily on the benefits associated with the wind power industry, however, as with any industry, these benefits come with certain limitations.

First, wind energy is not a type of dispatchable generation. Dispatchable generation can be defined as a type of power supply that can be turned on or off at the request of the operator, or "dispatched". Wind power can be viewed as an intermittent energy source, that places far less control is the hands of the operator as compared to other power generation methods, however it is possible to reduce electricity production.

Second, launching a wind farm comes with a very high initial capital investment cost. Even in a small-scale wind farm, the capital required to achieve any level of production is well into the millions of dollars.

Third, space requirements are a large drawback for any wind turbine installation project. These farms require vast amounts of open space, in areas with significant wind content to drive the system. For this reason, turbine farms are often located in very sparsely populated areas, outside of major urban centers. This places the source, and the demand point at which the energy will be consumed at very different geographic regions. For this reason, an additional investment in transmission infrastructure is needed to get the power from the turbine farms to the consumption areas.

Finally, wind turbines present a potential threat to local wildlife. During the construction phase, land is often disturbed, resulting in disrupted wildlife habitats. In operation, the turbines continue to result in a smaller disruption on the land area, however, pose a greater threat to birds as they can be killed by flying into the tower or a blade.

2.10 Fundamental Limitations of Wind Turbines

Betz Law, published in 1919 by German physicist Albert Betz, plays an important role in the capacity factor utilization of a wind turbine. Betz's law indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine. According to Betz's law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind. This factor, 16/27 (0.593), is known as Betz's coefficient. The technological advancement of the industry toward the Betz coefficient is ever-progressing, but still falls behind theoretical potential. The average capacity factor (which is calculated by dividing energy produced by production potential) is between 20% and 45% for onshore wind turbines and 40% to 50% for offshore wind turbines (Ragheb, 2014).

Not only is this energy production method intermittent, but there is also no way to economically store the energy produced. To provide some comparison, if we were to look at a comparable renewable energy generation technique such as hydropower, the energy has the potential to be stored. With the implementation of dams, the operator can collect a water reserve to hold for a period of time, and smooth out energy production levels. With wind power, the energy being generated cannot be stored, and thus must be consumed in the market immediately, or the turbines must be shut down.

Wind turbines are not a fully-efficient method of producing energy. In other words, all the energy captured from the wind is not necessarily what is going to be fed into the grid. The conversion efficiency of a common turbine is only about 80% to 90%, which means that about 10% to 20% of the captured energy is not converted into electricity. This lost energy can be primarily attributed to heat losses during production/conversion.

3. Additive Manufacturing

3.1 What is Additive Manufacturing?

3D Printing is a growing industry, which has numerous applications toward future supply chains in terms of cost savings benefits. Wohlers Report (2014) estimates that the global market size for 3D printing will grow from $3B USD in 2013 to $13B USD in 2018, and surpass $21B USD by 2020. According to Wohlers Report (2016), the additive manufacturing (AM) industry grew 25.9% (CAGR – Corporate Annual Growth Rate) to $5.165B USD in 2015. Gartner Inc. reports similar numbers, with a forecasted market size of $13B USD by 2018, additionally stating they expect 10% of oil and gas companies to be using 3D printing in their supply chains by 2019 (Moore, 2016). Furthermore, firms like Ford Motor Company, Boeing, Airbus, Lotus, BAE, Maersk, and General Electric are already using 3D printing technology in their manufacturing processes, in applications such as creating molds for casting, and rapid prototyping. By applying 3D printing technology (3DP) to the wind power sector, we feel we will be able to justify a transition to this new technology by shedding light on the many benefits that come with the adoption of the technology, including both economically justifiable benefits, and a variety of intangible factors.

To fully understand the applicability of 3D printing to the wind power sector, it is first necessary to identify the specific type of technology that would be ideally suited to this industry. Two umbrella terms can generally be applied to 3D printing technologies. The first, being “3D Printing”, or “3DP”, refers to the layer-by-layer creation of physical objects based on digital files (Petrick & Simpson, 2013). The term “Additive Manufacturing” is used to identify cases in which 3D printing technology is being used to create final parts or metallic components, the important factor being that they are geared toward final production. This can be further explained by viewing traditional manufacturing processes as “subtractive manufacturing”, where for instance, a large chunk of a natural resource is used at the start (ie. a piece of steel), after which a variety of techniques are used to subtract, or remove elements or pieces from this initial starting point, up until a functional final product is created that can be fed into the market. For the bulk of this research, the term additive manufacturing will be used.

The technology exists today to create products using additive manufacturing in ceramics, polymers, composites, and metals. Polymers most typically produce the most functional, finished products, requiring the least amount of post-production finishing, whereas metallic parts produced with 3D printing frequently require additional finishing and post-processing steps to achieve specified tolerances for use in real world situations. Additive manufacturing provides the opportunity to produce lightweight components, reduce manufacturing lead times, and decrease material wastage in the manufacturing process.

3.2 Additive Manufacturing Technologies

Although there are a variety of techniques within the additive manufacturing space, our research will focus only on the newest developments, currently capturing the most attention in the industry and with what we feel have the best potential to change the shape of the global manufacturing space. The following table summarizes the technologies we would like to place focus on:

Selective Laser Sintering (SLS)	A layer of powder is deposited on the build platform, after which a laser "draws" a single layer of the object into the powder. The build platform moves down, and more powder is added to draw the next layer.	Thermoplastics Metal Powders Ceramic Powders
Direct Metal Laser Sintering (DMLS)	Differs from SLS in that completely melted powder is deposited and builds a part with all the desirable properties of the original material.	Metal Powders Metal Alloys
Electron Beam Melting (EBM)	Fully dense metal components are built up, layer-by-layer, of metal powder, melted by a powerful electron beam. Each layer is melted to the exact geometry defined by a CAD model. The process takes place in vacuum and at high temperature, resulting in stress relieved components with material properties better than cast and comparable to wrought material.	Metal Powders Metal Alloys
Binder Jetting	A liquid binding agent is selectively deposited to join powder particles. Layers of material are then bonded to	Metal Powders

	form an object. The print head strategically drops binder into the powder. The job box lowers and another layer of powder is then spread and binder is added. Over time, the part develops through the layering of powder and binder.	Light Metals Cast Iron Steel Non-Ferrous Metals
Big Area Additive Manufacturing (BAAM)	Large scale additive manufacturing equipment designed to allow 3-D printing to be used for production manufacturing. The size and speed allow large parts to be made quickly. This technology is not as advanced in terms of the scope of materials that can be used for production, however the ability to use commodity thermoplastic materials means that the cost per part will be reasonable.	Plastics Polymers Resins

3.3 Why Additive Manufacturing?

The current environment of wind power is structured as such that wind farms are often very dispersed geographically, located in remote areas, away from city centers and manufacturing hubs. This is for a variety of reasons, including availability of land due to the grand scale of a wind farm, noise pollution due to the constant sound of the moving rotors, and a general interpretation of a wind farm near a small community being un-aesthetic. At present, when a windmill is manufactured, it is done at a central manufacturing facility, part-by-part, at which point the parts must be shipped to the planned farm location, and the windmill must be assembled. The same is the case for a part breakdown if a windmill were to fail. The part must then be manufactured again at a central location, and transported to the wind farm site location. This can often have an impact on power generation, and create downtime losses; a loss of revenue to the generation company. The cost of transportation can also be a very significant factor in most instances, as massive parts such as the blades must be loaded onto trucks, and driven hundreds of kilometers to sites that are not ideal logistically. Through additive manufacturing, we are able to manufacture parts, both for the initial build of the windmill, as well as spare parts for replacement in breakdown circumstances, in a more local environment, therefore reducing downtime losses and transportation costs in the process. Additive manufacturing presents an opportunity to disrupt what we believe as the standard, industry-accepted approach to the supply chain of wind power, and shift toward a local-for-local manufacturing environment. Through this research, we aim to determine whether additive manufacturing holds the potential to bring down the levelized cost of energy (LCOE) of wind power generation.

4. Literature Review

4.1 The Cost of Wind Power

When evaluating the cost of electricity produced by a wind turbine, there are a few key parameters to consider. These include (Gielen, 2012):

1. Investment costs (including project financing costs)
2. Operation and maintenance costs (fixed and variable)
3. Capacity factor (based on wind speeds and turbine availability factor)
4. Economic lifetime of the windmill
5. Cost of capital

The installed cost of a wind power project is dominated by the upfront capital cost (CapEx) of the wind turbines, and this can be as much as 84% of the total installed cost (Blanco, 2009; EWEA, 2009). The largest cost component for the turbine is the upper module, containing the rotor blades, tower, and gearbox - together these account for around 50-60% of the total turbine cost. Offshore wind farms are more expensive, but follow a different cost distribution, with the wind turbines accounting for 44-50% of the total cost. The generator, transformer, and power converter account for about 13% of the turbine costs. The balance of costs is allocated to “other”, which includes miscellaneous costs such as the rotor hub, cabling, and the rotor shaft. Grid connection, civil works, and other costs account for the balance to 100%. Connection costs (including electrical work, electricity lines, and the connection point) are typically 11-14% of the total capital cost of onshore wind farms, and 15-30% of offshore wind farms (Douglas-Westwood, 2010). Operations and maintenance costs typically account for 20-25% of the total LCOE of current wind power systems (EWEA, 2009).

In the beginning, this industry realized many opportunities to drive down the cost of wind power, primarily larger blades and higher hub heights. Between 2000 and 2002, turbine prices averaged at $700USD/kW (BNEF, 2011). Rising commodity prices during the period of 2006-2008 drove increased wind power costs, with the price of steel tripling between 2005 and it's peak in mid-2008 (Gielen, 2012). By 2009, prices had risen to $1500USD/kW in the USA, and $1800USD/kW in Europe. The installed cost of wind power projects based on 2011 data is in the range of $1,700 USD/kW to $2,150 USD/kW for onshore wind farms in developed countries (Wiser & Bolinger, 2011; IEA Wind, 2011). To compare, the installed cost of wind power projects based on 2014 data range from $850/kW to $1120/kW for utility-scale wind projects (Wiser & Bolinger, 2015). These figures show a positive trend in terms of cost reduction within industrial scale wind power development.

4.2 Breaking Down the Cost of Windmill Components

For the purpose of this research, we will use the component cost breakdown provided by the US Department of Energy (Mone, Stehley, Maples, & Settle, 2015b) as a baseline for our analysis. This can be outlined as follows:

Component	**Cost Share: Onshore**	**Cost Share: Offshore**
Turbine	71%	32.9%
Tower	13%	-
Nacelle	41%	-
Rotor	17%	-
Balance of System	20%	38.4%
Financial	9%	18.3%
Market Price Adjustment*	-	10.3%

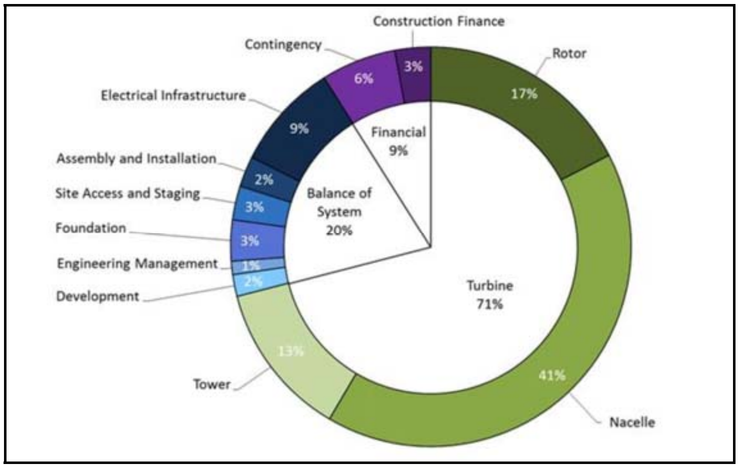
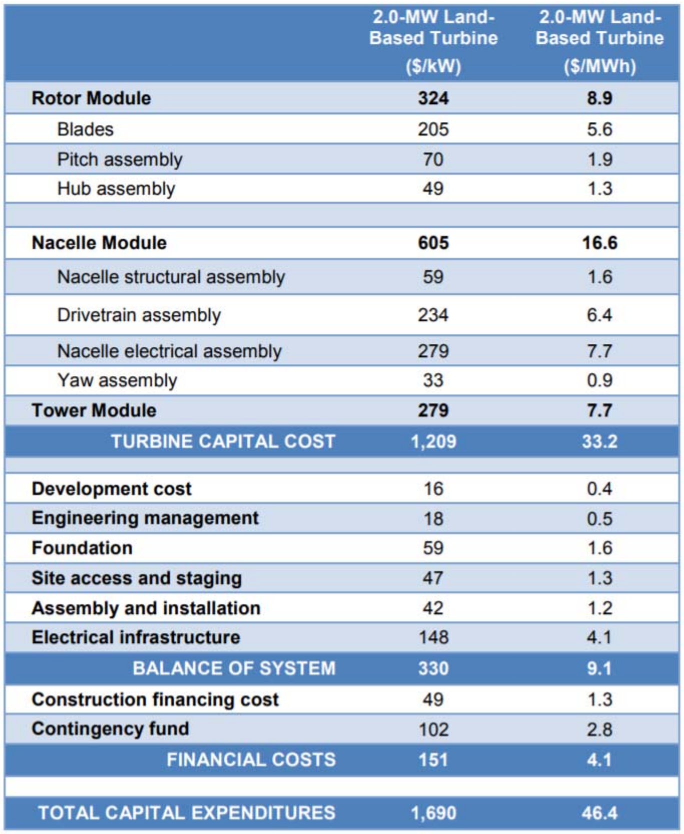


Figure 11: Breakdown of wind turbine capital costs, Source: NREL

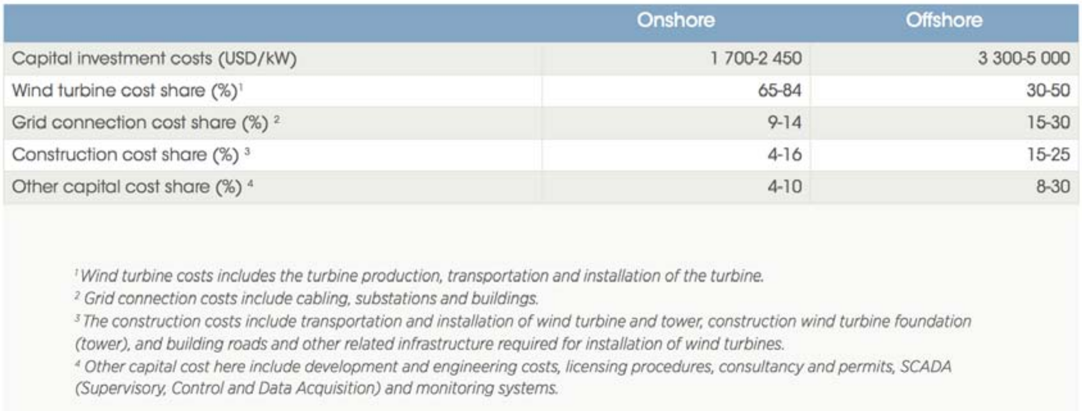


	2.0-MW Land-Based Turbine ($/kW)	2.0-MW Land-Based Turbine ($/MWh)
Rotor Module	**324**	**8.9**
Blades	205	5.6
Pitch assembly	70	1.9
Hub assembly	49	1.3
Nacelle Module	**605**	**16.6**
Nacelle structural assembly	59	1.6
Drivetrain assembly	234	6.4
Nacelle electrical assembly	279	7.7
Yaw assembly	33	0.9
Tower Module	**279**	**7.7**
TURBINE CAPITAL COST	**1,209**	**33.2**
Development cost	16	0.4
Engineering management	18	0.5
Foundation	59	1.6
Site access and staging	47	1.3
Assembly and installation	42	1.2
Electrical infrastructure	148	4.1
BALANCE OF SYSTEM	**330**	**9.1**
Construction financing cost	49	1.3
Contingency fund	102	2.8
FINANCIAL COSTS	**151**	**4.1**
TOTAL CAPITAL EXPENDITURES	**1,690**	**46.4**

Figure 12: Breakdown of Capital costs for a 2 MW turbine by total dollars and by per MW/h, Source: NREL

This has lead us to the conclusion that we should focus our research toward the onshore market, as the possible cost reduction for additive manufacturing is contained exclusively within the “turbine component”. This component represents 71% - 32.9% =

38.1% greater share of total windmill cost in the onshore scenario as compared to the offshore scenario. Figure 13 further illustrates our decision to pursue the turbine cost component of onshore wind farms:



	Onshore	Offshore
Capital investment costs (USD/kW)	1 700-2 450	3 300-5 000
Wind turbine cost share (%)[1]	65-84	30-50
Grid connection cost share (%) [2]	9-14	15-30
Construction cost share (%) [3]	4-16	15-25
Other capital cost share (%) [4]	4-10	8-30

[1] Wind turbine costs includes the turbine production, transportation and installation of the turbine.
[2] Grid connection costs include cabling, substations and buildings.
[3] The construction costs include transportation and installation of wind turbine and tower, construction wind turbine foundation (tower), and building roads and other related infrastructure required for installation of wind turbines.
[4] Other capital cost here include development and engineering costs, licensing procedures, consultancy and permits, SCADA (Supervisory, Control and Data Acquisition) and monitoring systems.

Figure 13: Onshore vs offshore cost comparison, Source: Blanco, 2009; EWEA, 2009; Douglas-Westwood, 2010; Make Consulting, 2011

4.3 Wind Turbine Manufacturing

A modern wind turbine consists of more than 8,000 different components (AWEA, 2016). The turbine can be divided into 3 primary sections, this includes the rotor, nacelle, and tower sections. The largest, but most simple of the 3 is the tower. The tower section is made primarily of concrete at the base, and rolled steel in the shaft, with the sole function of holding up the nacelle and rotor. The nacelle is a shell or dome, which contains and shields the internal components from the external environment. The components inside of the nacelle are mainly concerned with the conversion of mechanical energy into electrical energy. The shell of the nacelle is made primarily of fibreglass, while the components inside the nacelle can vary between aluminium, cast iron, copper, plastic, stainless steel, and steel alloys. The final section of the turbine, or the rotors, are comprised of 4 major components. These include the blades, blade extender, hub, and pitch drive system. Blades are made of fibreglass reinforced plastics, blade extenders are made of steel, the hub is made of cast iron, and the pitch drive system is made using a combination of stainless steel and steel alloys (Wilburn, 2011).

Understanding the materials in the finished product helps to provide insight into the possible types of manufacturing that are used and potential uses of additive manufacturing. Below is an overview of the material composition of a wind turbine by weight:

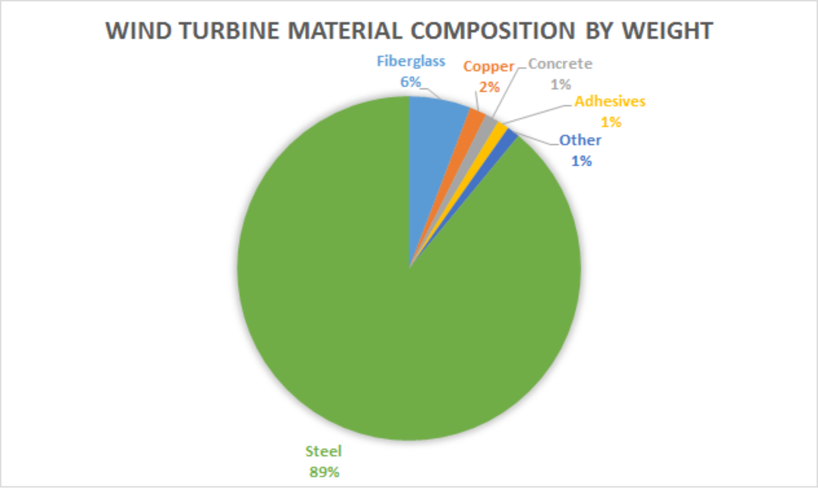


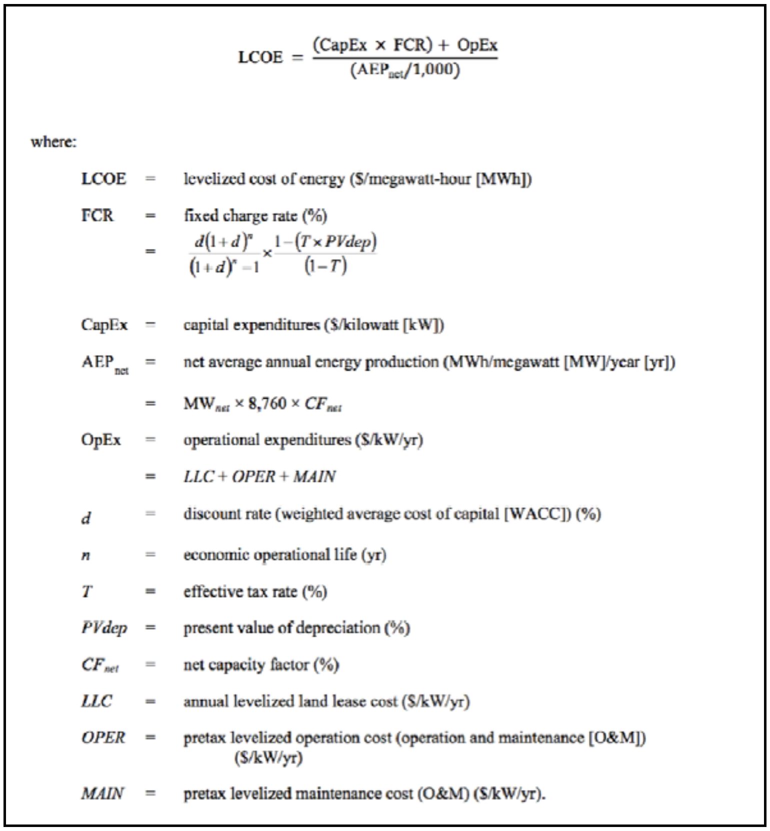
Figure 14: Wind turbine material composition by weight, Source: Wilburn, 2011

It is very evident that the main material used in a wind turbine is steel which is utilized in the tower and many of the components (Figure 14). It is worth noting that the high density of steel (at 8,000 kg/m^3) as compared to glass reinforced plastic (Fiberglass) (at 1,450 kg/m^3) (Amiantit Industrial, 2009) is a major contributing factor toward the material composition by weight graphic presented above.

The most unique component and the largest single component in a wind turbine are the blades. Although it is impossible to know for certain, turbine blades are likely the largest objects made of fiberglass. Since the manufacturing of large scale fiberglass objects has not been used in other industries and that fiberglass often requires a significant amount of manual labour, it appears to be an excellent candidate for automation.

4.4 The Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is often cited as a convenient summary measure of the overall competitiveness of different generating technologies. It represents the per-megawatt-hour cost (in real dollars) of building and operating a generating plant over an assumed financial life cycle (Mone et al., 2015b). Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type. For the purpose of this research, we will use the following formula to derive the LCOE of a windmill:



$$\text{LCOE} = \frac{(\text{CapEx} \times \text{FCR}) + \text{OpEx}}{(\text{AEP}_{\text{net}}/1{,}000)}$$

where:

LCOE = levelized cost of energy (\$/megawatt-hour [MWh])

FCR = fixed charge rate (%)

$= \frac{d(1+d)^n}{(1+d)^n - 1} \times \frac{1-(T \times PVdep)}{(1-T)}$

CapEx = capital expenditures (\$/kilowatt [kW])

AEP_{net} = net average annual energy production (MWh/megawatt [MW]/year [yr])

$= \text{MW}_{net} \times 8{,}760 \times CF_{net}$

OpEx = operational expenditures (\$/kW/yr)

$= LLC + OPER + MAIN$

d = discount rate (weighted average cost of capital [WACC]) (%)

n = economic operational life (yr)

T = effective tax rate (%)

$PVdep$ = present value of depreciation (%)

CF_{net} = net capacity factor (%)

LLC = annual levelized land lease cost (\$/kW/yr)

$OPER$ = pretax levelized operation cost (operation and maintenance [O&M]) (\$/kW/yr)

$MAIN$ = pretax levelized maintenance cost (O&M) (\$/kW/yr).

Eq 2: Wind Power LCOE, Source: NREL

The basic inputs of the LCOE equation are:

- CapEx → Capital Expenditures
- OpEx → Operational Expenditures
    - Generally expressed in 2 categories:
        - OPER or Fixed Operations: Includes discrete, known operations costs (scheduled plant maintenance, rent, land lease cost, taxes, utilities, insurance payments) that typically do not change depending on how much electricity is generated
        - MAIN or Variable OpEx: Includes unplanned maintenance of either the plant or turbine, planned turbine maintenance, and other costs that may vary throughout the project life depending on how much electricity is generated
- AEP → Annual Energy Production
    - Enables the model to capture system-level impacts from design changes, ie. turbine height
- FCR → A Fixed Charge Rate
    - Represents the amount of revenue required to pay the carrying charges as applied to the CapEx on that investment during the expected project life on an annual basis

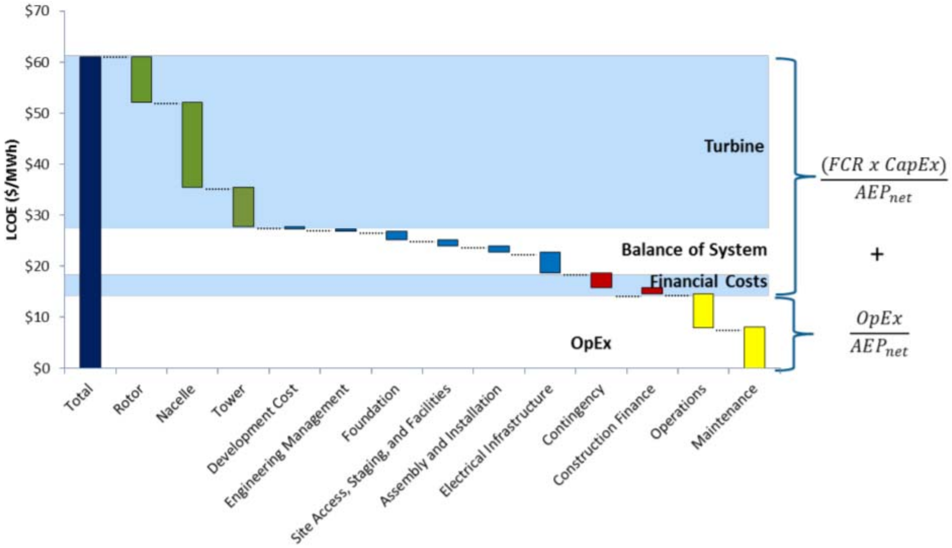


Figure 15: Detailed breakdown of wind energy LCOE, Source: NREL

For our analysis, we will assume a 20-year project life cycle to be applied to the wind farms. Because of CapEx variability, a market price adjustment can be applied to bring the CapEx cost in line with the reported industry average. The market price adjustment accounts for fluctuations in component costs, profit margins, foreign exchange rates, supply chain constraints, and other market conditions that can vary from project to project. Each actual project has a unique risk profile, financing terms, and ownership structure. The after-tax WACC is used for assessing the appropriate discount rate.

We can compare this to the LCOE of other electricity generation types both renewable and non-renewable which include fuel costs added to the formula. Figure 16 highlights some of these cost comparisons between major types of electricity generation.

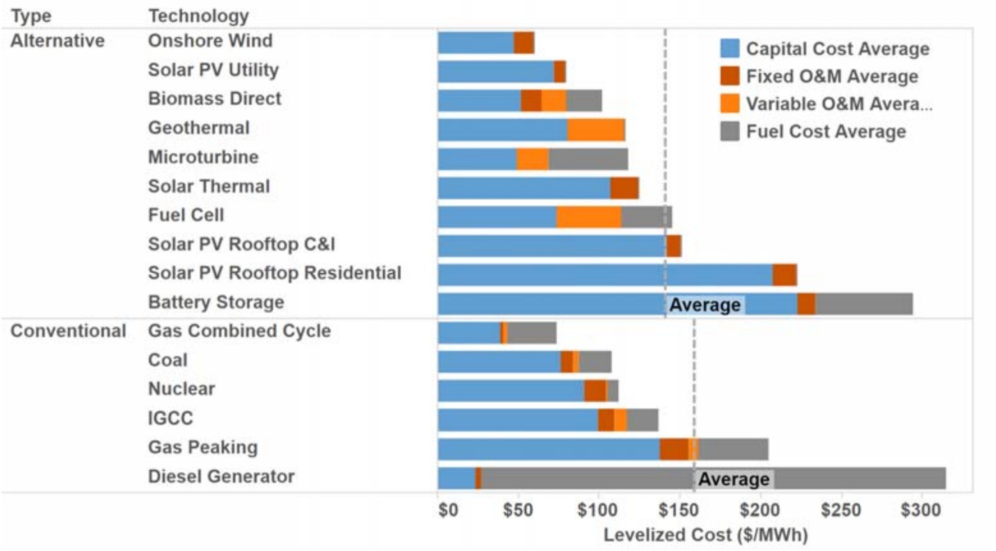


Figure 16: Cost by type of onshore wind compared to other energy generation types, Source: Energy Innovation LLC, 2015

Figure 16 highlights that proportion of costs is similarly in line with others in the alternative or renewable types, differing mostly from the generation types that require a fuel input. Wind energy's operations and maintenance costs are also largely fixed rather than variable with production as compared to most of its competitors.

4.5 The Effect of Changes to Variables on the LCOE

Each variable in the LCOE (Levelized Cost of Energy) as described can vary based on local wind environment, efficiency of blades & turbine, capital expenses, and operating expenses. Figure 16 highlights the effect of a 1% change on each of the 3 key variables Capacity factor or AEP, initial capital expenditures, and annual operational costs. This is done by using Figure 15's and NREL's 2015 Cost of Wind Energy Review capacity factor assumptions (0,399) as a baseline. The slope of these lines indicates how sensitive the LCOE is to each of these variables.

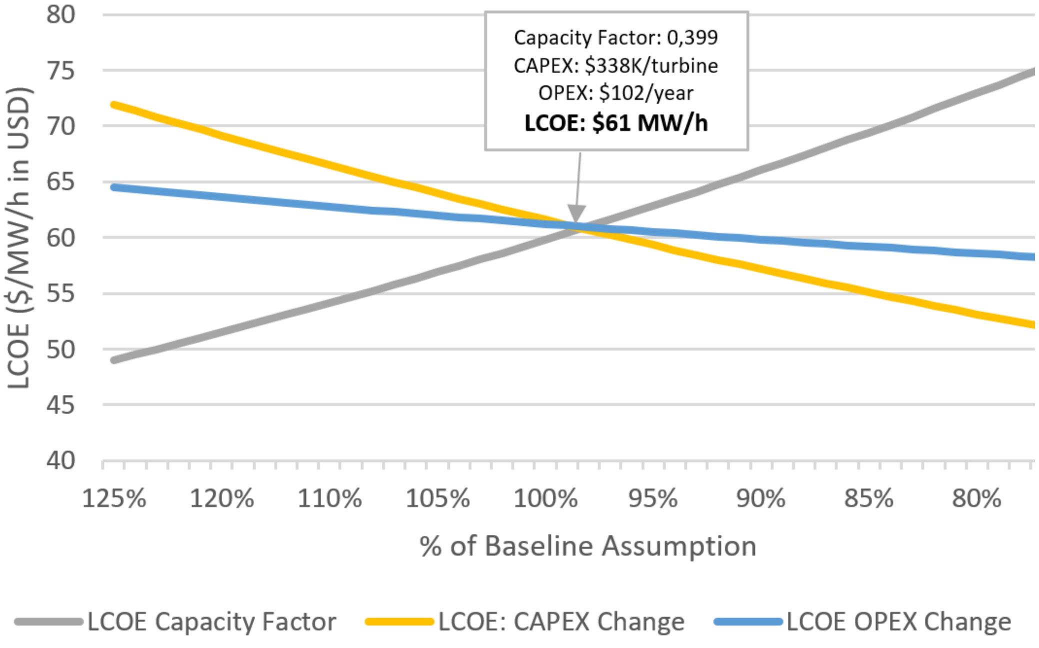


Figure 17: Sensitivity analysis comparison between major components of the LCOE, Created by authors

Our findings are consistent with that of the NREL's sensitivity analysis (Figure 18) but highlight them in a different perspective. Both sensitivity analysis' highlight the importance of capacity factor and CapEx as the primary drivers for the LCOE.

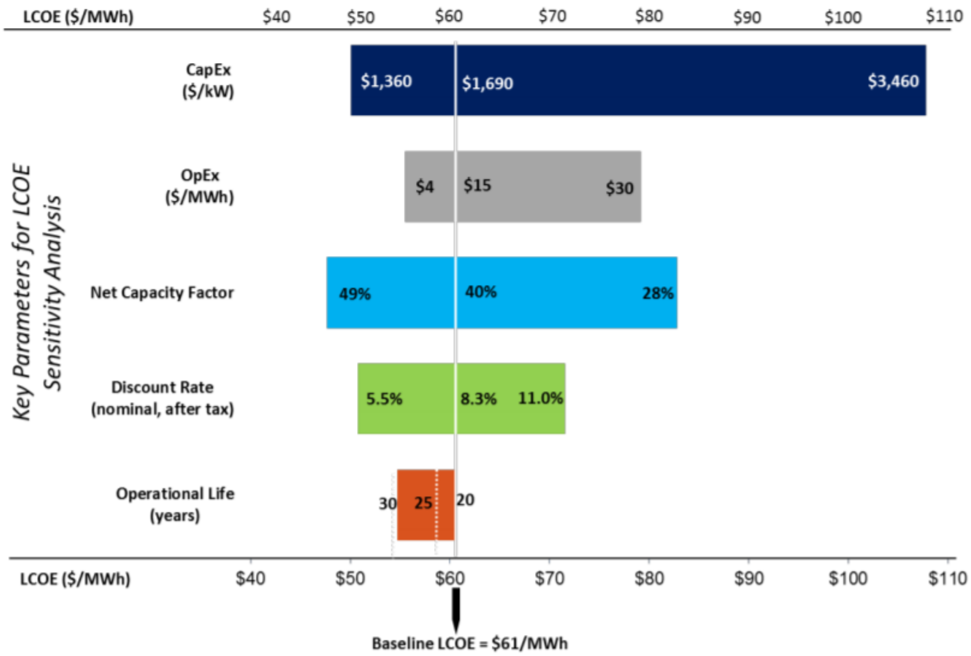
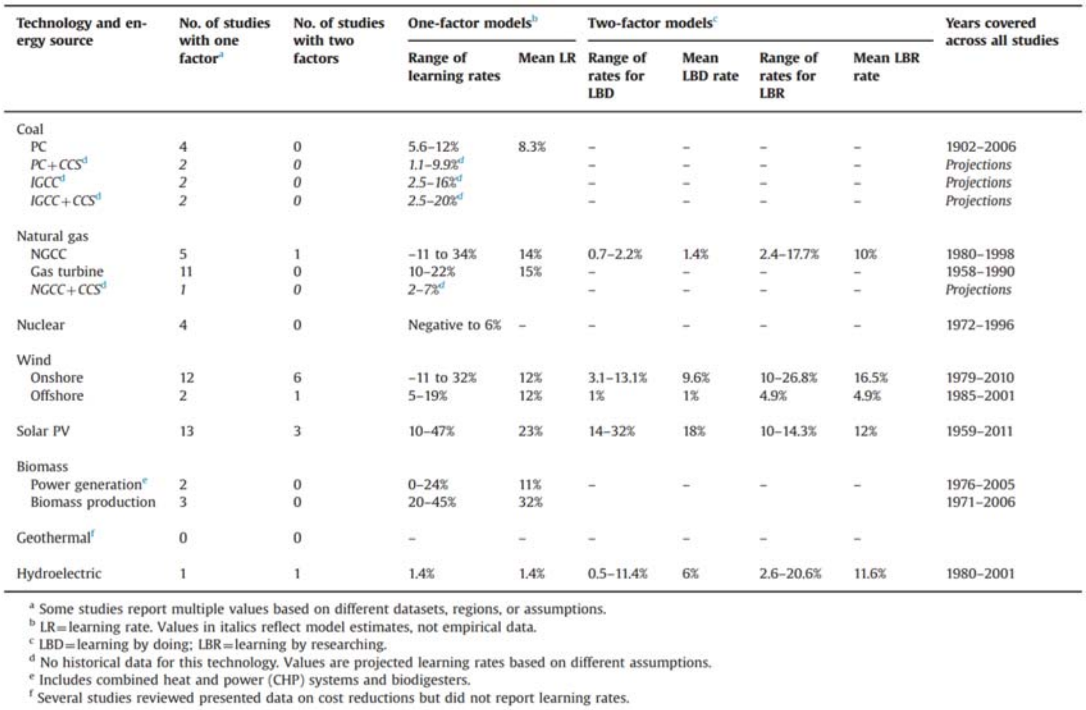


Figure 18: Sensitivity Analysis performed by NREL on Key parameters, Source: NREL

4.6 Learning Rates and the Wind Power Industry

The term learning rate refers to the fact that as we produce more of something we get a better understanding of it, and learn how to produce it cheaper, and more efficiently. The purpose of learning rates is to give further information to policy makers in aiding with the decision of future energy supply strategies. The term learning rate refers to the fractional cost reduction of the LCOE by a type of energy for each doubling of cumulative production or capacity of that technology (Rubin, Azevedo, Jamarillo & Yeh, 2015). As introduced previously the estimates by the Global Wind Energy Council expect wind power capacities to double in 2020 compared to 2014 levels (Figure 5). A low learning rate therefore implies that a technology has reached maturity and there is little improvement believed to be available to further reduce the cost. A high learning rate implies that a technology has more room for improvement and therefore more cost reductions. Learning rates differ greatly based on methodology of study however can still help indicate a general sense of a technology's maturity level.



Technology and energy source	No. of studies with one factor[a]	No. of studies with two factors	One-factor models[b]		Two-factor models[c]				Years covered across all studies
			Range of learning rates	Mean LR	Range of rates for LBD	Mean LBD rate	Range of rates for LBR	Mean LBR rate	
Coal									
PC	4	0	5.6–12%	8.3%	–	–	–	–	1902–2006
PC+CCS[d]	*2*	*0*	*1.1–9.9%*[d]		–	–	–	–	*Projections*
IGCC[d]	*2*	*0*	*2.5–16%*[d]		–	–	–	–	*Projections*
IGCC+CCS[d]	*2*	*0*	*2.5–20%*[d]		–	–	–	–	*Projections*
Natural gas									
NGCC	5	1	–11 to 34%	14%	0.7–2.2%	1.4%	2.4–17.7%	10%	1980–1998
Gas turbine	11	0	10–22%	15%	–	–	–	–	1958–1990
NGCC+CCS[d]	*1*	*0*	*2–7%*[d]		–	–	–	–	*Projections*
Nuclear	4	0	Negative to 6%	–	–	–	–	–	1972–1996
Wind									
Onshore	12	6	–11 to 32%	12%	3.1–13.1%	9.6%	10–26.8%	16.5%	1979–2010
Offshore	2	1	5–19%	12%	1%	1%	4.9%	4.9%	1985–2001
Solar PV	13	3	10–47%	23%	14–32%	18%	10–14.3%	12%	1959–2011
Biomass									
Power generation[e]	2	0	0–24%	11%	–	–	–	–	1976–2005
Biomass production	3	0	20–45%	32%					1971–2006
Geothermal[f]	0	0	–	–	–	–	–	–	
Hydroelectric	1	1	1.4%	1.4%	0.5–11.4%	6%	2.6–20.6%	11.6%	1980–2001

[a] Some studies report multiple values based on different datasets, regions, or assumptions.
[b] LR=learning rate. Values in italics reflect model estimates, not empirical data.
[c] LBD=learning by doing; LBR=learning by researching.
[d] No historical data for this technology. Values are projected learning rates based on different assumptions.
[e] Includes combined heat and power (CHP) systems and biodigesters.
[f] Several studies reviewed presented data on cost reductions but did not report learning rates.

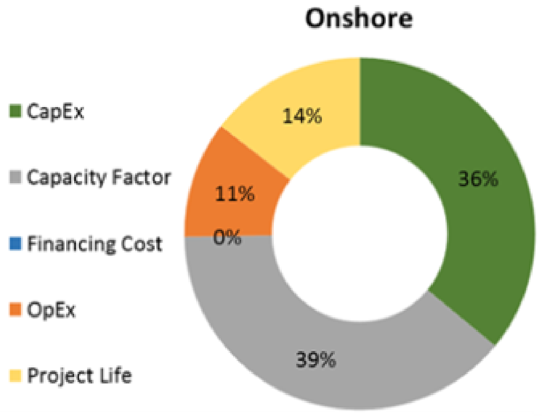
Figure 19: Review of learning rates by technology and study, Source: Rubin et al., 2015

As shown by the study by Rubin et al., learning rates in energy differ greatly by technology and methodology of study. The key take-away is that wind energy both onshore and offshore both have higher learning rates than many of their competing technologies.

According to IRENA "The largest cost reductions will therefore come from learning effects in wind turbine manufacturing, with smaller, but important contributions from the remaining areas" (IRENA, 2012). This is a clear statement that manufacturing innovation will lead to a lower overall LCOE; therefore, additive manufacturing, a technology that is new to this large-scale industry could present opportunities for reducing manufacturing costs.

4.7 Expert Analysis on the Future Development of LCOE

As an alternative view to the learning curve for projecting future wind energy costs, an elicitation from wind energy experts was made in 2016 and 163 individuals from around the globe responded. The survey's purpose was to get an understanding of what experts believe about the future cost of wind energy. The median response in predicted LCOE (Figure 21) is also consistent with the learning rate in the Rubin et al. study (Figure 19) at a predicted 10% decrease by 2020 when cumulative capacities are expected to double relative to 2014 capacities (highlighted in Figure 5). Key findings from the survey indicate that experts believe that both onshore wind energy costs will come down in the future and this will come primarily as a result of reduced capital expenditure costs, increased capacity factors and increased turbine lifetime. Furthermore, experts surveyed predict that blade size and design will have the greatest impact on cost reduction. This implying that blade designs and lengths will be changing over the coming years. Figure 20 & 21 is a summary of the experts' predictions.



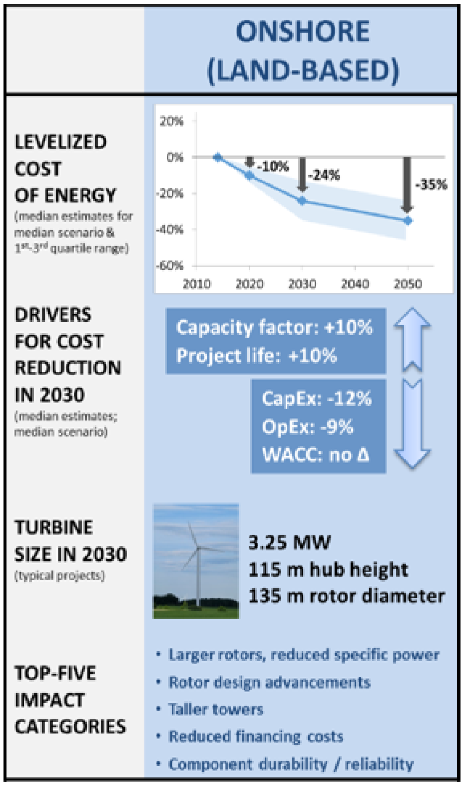


Figure 20 (left): Relative impact drivers for Median-Scenario LCOE Reduction for onshore wind energy.

Figure 21 (right): Key findings on Onshore (Land-Based), Source: Wiser et al., 2016

4.8 Blade Design

The design of the blade is of utmost importance for determining the amount of energy harnessed by the wind and therefore the LCOE of electricity production. Blade design needs to be as light as possible, minimizing materials and operational costs, however this needs to be done without sacrificing the strength or integrity of the blade or it's generation ability. This is further emphasized by a quote from Kevin Standish, an engineering manager at Siemens Wind Power when he says, "The rotor produces 100% of the energy, so if you can come up with innovative, new technologies or blade design features, you are directly impacting the cost of wind power" (World Wind Technology, 2016). Blade erosion over time is a common concern in the wind power market today, as it reduces aerodynamic performance and structural integrity, which has a direct effect on energy captured. In order to mitigate these situations, a company may look to a temporary fix, for example, the use of protective tape, or a longer-term fix, including blade refurbishment, or a complete change-out of the worn blade. For these reasons, innovation in blade manufacturing and design to reduce wear, reduce production time, or reduce manufacturing cost would have a positive impact on the supply chain of the wind power industry.

Blade making has migrated toward processes that minimize cycle time and reduce both cost and the probability of defects. This drive for innovation has seen a number of new technologies being implemented in blade design over the past several years, including Prepreg (pre-impregnated), Automated Tape Layup (ATL), and Automated Fibre Placement (AFP). Input materials, however, have not evolved so rapidly, with fibreglass shells, epoxy resins, and wood/foam cores remaining the norm for a long period of time (Watson & Serrano, 2010). A recent trend in the blade industry is heading towards the use of carbon fibre in complete or in hybrid use with fiberglass (Gurit, 2017). Using carbon fiber is more expensive but results in higher efficiency from the blades due to less rotating mass as carbon fiber is lighter and can enable towers and other components of the turbine to be manufactured with lower strength demands and therefore at lower costs due to reduced stresses from lighter blades. Carbon fiber also enables blades to have an increased range of profiles since it is stronger than fiberglass and can therefore be made thinner.

4.9 Advantages of Additive Manufacturing

Additive manufacturing provides designers freedom from the constraints of traditional processes; some even argue that it flips the traditional “design for manufacturing” approach toward a “manufacturing for design” style (Beaman, 2013). Lipson & Kurman (2013) state “bursts of innovation happen when an emerging technology removes a once prohibitive barrier of cost, distance, or time”. Through the application of additive manufacturing, we are provided the opportunity to (a) remove the cost barrier of traditional fixed-equipment manufacturing, (b) remove the distance barrier raised by widely distributed suppliers sourced based on cost, and (c) reduce the time barrier through a tighter coupling of design and production in an experimental fashion. Additive manufacturing is identified to cost-effectively lower manufacturing inputs and outputs in markets with low volume, customized, and high-value production chains (Gebler, Uiterkamp, & Visser, 2014).

Additive manufacturing technology allows for printing of parts comprised of highly complex geometries. Many businesses are using additive manufacturing for benefits like “complexity-for-free manufacturing”. In traditional manufacturing, there exists a direct connection between complexity and manufacturing costs. A relationship tying cost to complexity does not exist in AM (Lindemann, Jahnke, Moi, & Koch, 2012). There exists an opportunity in additive manufacturing for an increase in diversity of variants, while quantity of variants decreases.

One important characteristic is its ability to reduce, or completely remove the economies of scale that would be present in traditional manufacturing processes. This is due to the only inputs in the manufacturing process being the cost of the printer’s build time, and the material to be used for fabrication. For this reason, you are able to achieve a similar unit cost whether you are printing 5 units or 500. Designs intended for traditional manufacturing are often heavily limited by high costs in construction and tool-making. With additive manufacturing, there is no need to produce any kind of tools for fabrication (ie. forming tools). Since there is no need for tooling for production of spare parts, it is unnecessary to hold legacy tooling in storage. There is also no need to produce a high amount of an individual part to refinance the tools, like in traditional manufacturing. The targeted design of a relieved or decreased assembly process may result in a much higher reduction of the production costs when compared to the construction of parts designed for traditional manufacturing (Lindemann et al., 2012). Some other, more intangible benefits, include the potential to lower energy use, resource demands, and related CO2 emissions over the entire product life cycle, induce changes in labour structures, and generate shifts toward more digital and localized supply chains.

Some important characteristics of additive manufacturing are outlined by Mohr & Khan (2015):

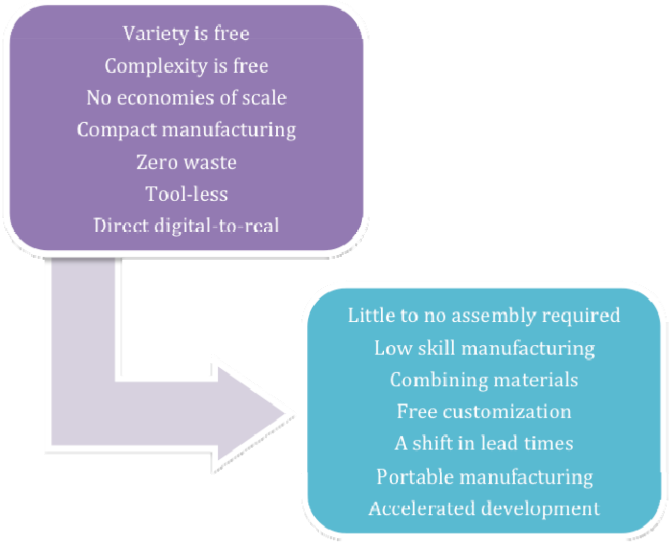


Figure 22: Important Characteristics of Additive Manufacturing and Their Implications, Source: Created by Authors

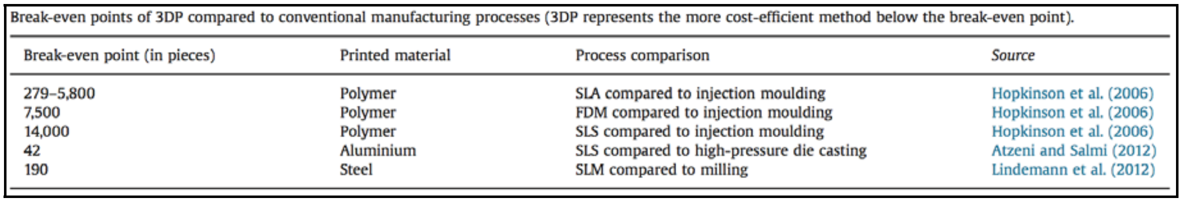
If taken further to implications directly relating to the disruption of the traditional supply chain through additive manufacturing, Mohr & Khan (2015) give examples including:

Figure 23: Disrupting the Supply Chain of Conventional Manufacturing - Implications of AM, Source: Created by Authors

These examples all illustrate that the industrial application of additive manufacturing holds true potential to disrupt the traditional manufacturing and supply chain structure. By creating a high ratio of volume to production space required, additive manufacturing becomes a favorable option for applications constrained to the limitation of available space. However, due to still currently high prices on input materials, the cost of additive manufacturing is being deterred from driving down manufacturing costs even further. As more material is sold every year, more manufacturers will enter the market and the costs for the material, which in some cases (ie. titanium), are approximately 10x more expensive than traditional materials, will decrease in the future (Lindemann et al., 2012). Additive manufacturing makes it possible to break the constraints caused by traditional tooling. With additive manufacturing, it is possible to design a part with unlimited complexity, allowing twisted and contorted shapes, blind holes and screws, and a very high strength-to-weight ratio (Atzeni & Salmi, 2012).

4.10 Breaking Down the Cost of Additive Manufacturing

Continual advancements in additive manufacturing continue to push the technology toward a state where it can be viewed as a suitable alternative to traditional milling or die casting. One advantage of the technology is the minimal input factors required to produce an end product. After comparing approaches taken by past researchers, we have been able to conclude that most commonly, production cost using additive manufacturing can be broken down into 3 components; (1) fixed cost, like labour and utilities, (2) variable cost, or the input material to be used for production, and (3) a machine hourly rate, used to account for build time and allocation of the capital investment. We will also assume factors such as gases, compressed air, and water cooling requirements to be negligible. If taken further, these factors can then be combined to determine a break-even point where the cost savings of using additive manufacturing would then surpass traditional manufacturing methods. The below table provided by the (Gebler et al., 2014) summarizes the break-even point of various additive manufacturing techniques.



Break-even points of 3DP compared to conventional manufacturing processes (3DP represents the more cost-efficient method below the break-even point).

Break-even point (in pieces)	Printed material	Process comparison	*Source*
279–5,800	Polymer	SLA compared to injection moulding	Hopkinson et al. (2006)
7,500	Polymer	FDM compared to injection moulding	Hopkinson et al. (2006)
14,000	Polymer	SLS compared to injection moulding	Hopkinson et al. (2006)
42	Aluminium	SLS compared to high-pressure die casting	Atzeni and Salmi (2012)
190	Steel	SLM compared to milling	Lindemann et al. (2012)

Figure 24: Break-Even Points of Additive Manufacturing Technologies, Source: Gebler et al., 2014

One approach to deriving a unit cost using additive manufacturing is presented by Atzeni & Salmi (2012). Their research states that the cost of an additive manufactured part can be divided into 4 items:

1. Material Cost
2. Pre-Processing Cost
3. Processing Cost
4. Post-Processing Cost

Their research explains that regarding material cost, volume is usually increased by 10% in cost analysis to take account of support and waste. In the case of traditional manufacturing, the mold/die cost is attributable to approximately 90% of the total manufacturing cost of the end product, followed by the post-processing cost (8%) - the actual commodity cost is marginal (Atzeni & Salmi, 2012). In the case of AM fabrication, the authors state that about 90% of the component cost is attributable to machine depreciation, because of the very high capital investment cost. The remaining cost is due to material. Their estimated hourly cost for an operator of AM machinery ranges from 20 to 35 euros according to skills required. As most of the skill is required for part design in the digital file, there is not a large expertise requirement for operating the machinery.

Lindemann et al. (2012) have a different cost allocation methodology, stating that they attribute machine costs at 73%, material costs at 12%, and the remaining due to a variety of additional factors. As the process is a fully automated “lights out” process, it is logical that the machine rate costs have the greatest contribution to the total costs of a build. The authors state that build cost is a factor of fixed costs, a machine hourly rate, and a product build time. They also state that the aggregate material cost is more than just the material input required to fabrication the product, but a factor of material price, mass density, cost of support structures, a material waste rate, part volume, and the number of parts being produced.

$$\boxed{\text{Costs}_{\text{Build}} = \text{Costs}_{\text{Fixed}} + \text{MachineHourlyRate} * \text{Buildtime}}$$

$$\boxed{\begin{aligned}\text{MaterialCost} = {} & \text{Supportstucture} * \text{Wastefactor} * \text{Number of Parts} * \text{Partsvolume} \\ & * \text{MaterialPrice} * \text{MassDensity}\end{aligned}}$$

Eq. 3 & 4: Breaking Down the Cost of Additive Manufacturing, Source: Lindemann et al., 2012

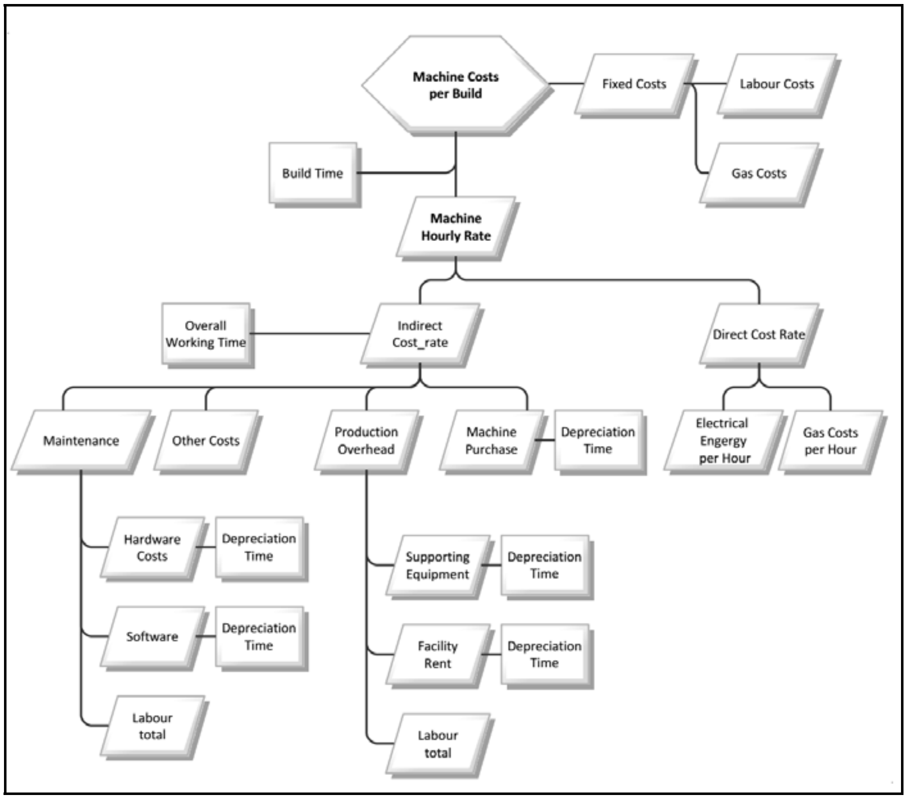


Figure 25: Determining the Cost of Additive Manufacturing, Source: Lindemann et al., 2012

4.11 Big Area Additive Manufacturing (BAAM)

As part of this research, it is important to note the limitation associated with resource availability. Currently, there are very few 3D printing units that are able to handle printing parts on such a large scale that are required for manufacturing wind turbine parts. The following table summarizes some of the industry-leading 3D printers in terms of build volume that are currently widely available for purchase:

Manufacturer	**Model**	**Technology**	**Build Envelope Size**	**Build Speed**
SLM Solutions	SLM500HL	DMLS	50 x 28 x 36.5 cm	105 ccm/hour
EOS	M400	DMLS	40 x 40 x 40 cm	0.5 ccm/hour
3D Systems	ProX DMP320	DMLS	27.5 x 27.5 x 42 cm	Unknown
ExOne	EXERIAL	Binder Jetting	220 x 120 x 70 cm	30-40 ccm/hour
Arcam	Q20Plus	EBM	35 x 38 cm (ovular)	80 ccm/hour

Many technology research firms have recently been putting serious time and investment into creating machinery that is able to fabricate parts much larger than these widely available printers, known at Big Area Additive Manufacturing (BAAM). The aim of BAAM is to create large-scale 3D printed products in a matter of hours, achieving build speeds much greater than current market technologies allow. We have identified the following 3 units to be the most feasible for the fabrication of wind turbine parts:

Manufacturer	**Build Envelope Size**	**Build Speed**	**Maximum Weight**
Cincinnati Incorporated	10.8 x 3.9 x 4.4 meters	45 kg/hour	18,144 kg
Thermwood	2.4 x 1.8 x 6.1 meters	45 kg/hour	*not stated
Ingersoll	7 x 3 x 14 meters	450 kg/hour	*not stated

4.12 Applying Additive Manufacturing to Wind Power

A windmill can be broken down into a variety of components, however, not all of these components have the potential to be manufactured using additive manufacturing techniques. Through interviews with a variety of wind turbine experts combined with a detailed breakdown of all wind turbine parts provided by the US National Renewable Energy Laboratory (Mone, Smith, Maples, & Hand, 2015a), we were able to form the following table to outline our assumptions toward the feasibility of each part to be produced using additive manufacturing, including a description of each of the component parts:

Component	**Description**	**Suitable for Additive Manufacturing?**
Anemometer	Measures the wind speed and transmits wind speed data to the controller	No
Blades	Lifts and rotates when wind is blown over them, causing the rotor to spin	Yes
Brakes	Stops the rotor mechanically, electrically, or hydraulically, in emergencies	Yes
Controller	Starts up the machine at wind speeds of about 8 to 16 miles per hour and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they may be damaged by the high winds	No
Gearbox	Connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 30-60 rotations per minute (rpm), to about 1,000-1,800 rpm; this is the rotational speed required by most generators to produce electricity	Yes
Generator	Produces 60-cycle AC electricity; it is usually an off-the-shelf induction generator	No

High-Speed Shaft	Drives the generator	Yes
Low-Speed Shaft	Turns the low-speed shaft at about 30-60 rpm	Yes
Nacelle	Sits atop the tower and contains the gearbox, low- and high-speed shafts, generator, controller, and brake	Yes
Pitch	Turns (or pitches) blades out of the wind to control the rotor speed, and to keep the rotor from turning in winds that are too high or too low to produce electricity	No
Rotor	Blades and hub together form the rotor	Yes
Tower	Made from tubular steel, concrete, or steel lattice. Supports the structure of the turbine. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity	Maybe (size could be an issue)
Wind Vane	Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind	No
Yaw Drive	Orients upwind turbines to keep them facing the wind when the direction changes. Downwind turbines don't require a yaw drive because the wind manually blows the rotor away from it	Yes
Yaw Motor	Powers the yaw drive	No

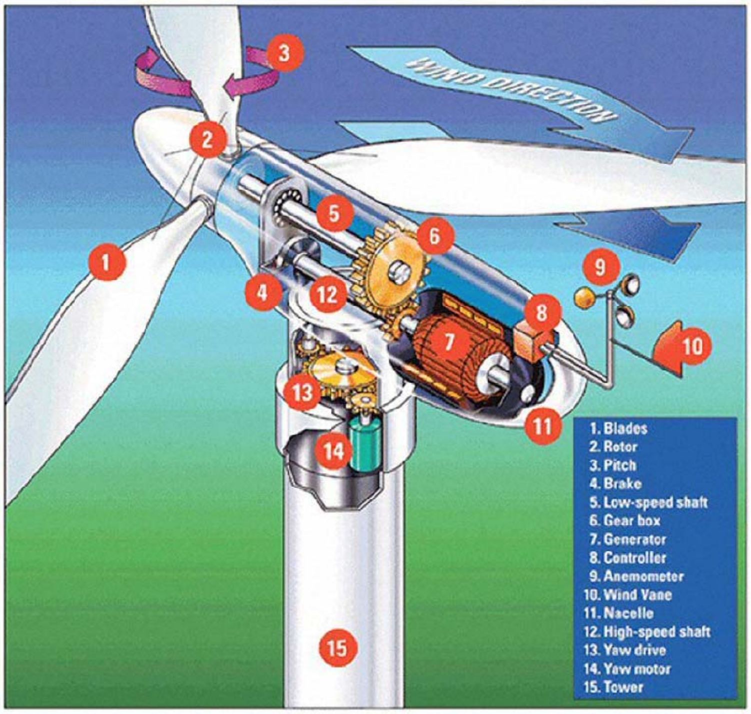


Figure 26: The Parts in a Wind Turbine, Source: German Wind Energy Association

4.13 Supply Chain Drivers and Strategic Fit

Strategic fit is an important consideration when trying to apply a new innovation to the existing supply chain of a mature industry like wind turbine manufacturing. As emphasized by Chopra & Meindl (2010), in order to achieve strategic fit within a supply chain, there must be a balance between responsiveness and efficiency that best supports the company's competitive strategy. They go on to say that the responsiveness and efficiency of a particular supply chain can be measured based upon the interaction between the following logistical and cross-functional drivers of supply chain performance:

1. Facilities
2. Inventory
3. Transportation
4. Information
5. Sourcing
6. Pricing

These drivers can then be further categorized into the logistical or cross-functional, as emphasized by the following graphic:

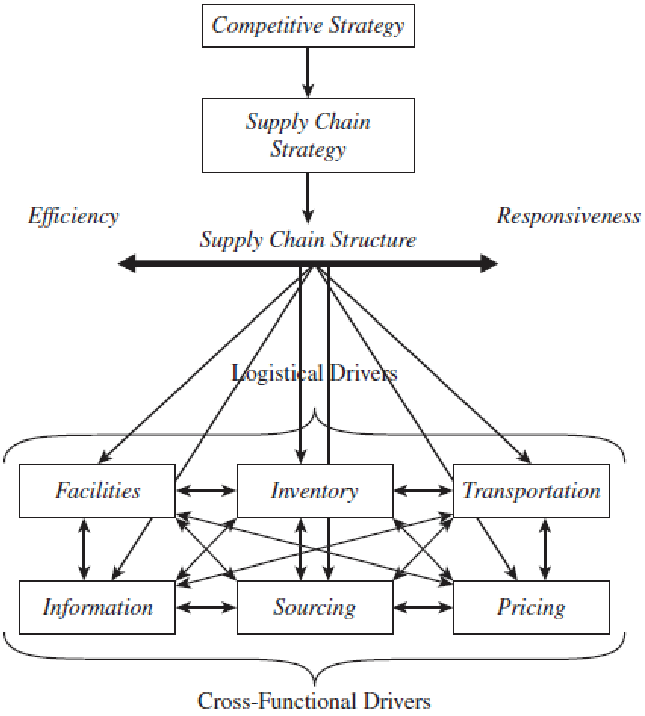


Figure 27: Supply Chain Drivers of Strategic Fit, Source: (Chopra & Meindl, 2010)

Facilities (1) can be divided into either production or storage sites. When analyzing the facility driver, it is important to look at the role each facility will play, their location in relation to the final markets they will serve, overall capacity of the facilities, and the flexibility of either production or storage at each location. Sub-components of the inventory driver (2) can be divided into raw material inputs, work-in-process parts, and finished goods within the supply chain. The transportation (3) driver analyzes the interaction between each route and node within the supply chain, with emphasis that each route/node will have its own challenges and performance characteristics. Information (4), which can be viewed as the most important driver of the supply chain, relates to the flow of data between all participating parties, whether it be data and analysis regarding inventory levels, costs, prices, customers, or facilities flowing inside the supply chain. Sourcing (5) determines which activities along the supply chain will be allocated to which parties. This brings into concern which tasks will be done internally, and which will be outsourced. Sourcing decisions will have a strategic impact on both the supply chain responsiveness and efficiency. Pricing (6) will be a driver of supply chain demand, determining what a firm will charge for a particular good or service. This can be extended to the customer level, where a customer who values responsiveness over efficiency may hold off longer to order a particular product, but may be willing to pay a premium for this increased responsiveness, whereas a customer who places greater value on efficiency may order earlier, and be less willing to pay a premium price.

4.14 The Logistics of Wind Power

For the purpose of this thesis, we would like to place emphasis on the logistical drivers of supply chain performance, and analyze how these would be affected by a transition from traditional production methods toward additive manufacturing. In terms of logistics, the wind turbine supply chain market can be best characterized as a crossover between container shipping, air freight, logistics, port services, offshore, break-bulk, and project cargo in and end-to-end multi-modal chain (Poulsen, Rytter, & Chen, 2013). In the wind power market, each wind farm project is tailor-made, often requiring its own set of logistics and shipping solutions, and having its own supply chain management challenges. This is due to the geographic and topographic variances between potential sites, ranging between windy and mountainous regions, to flat prairies. Schuh & Weinholdt (2011) point out that many companies in the wind power industry have not yet implemented spare parts management strategies and they apply system dynamics simulation methods to support decisions on such implementations for a supply chain. The size and weight of wind turbine parts put great stress on logistics operations through all supply chain nodes.

Some of the costs in a common wind farm supply chain include the cost of cranes, railways, trucking, storage/warehouse spaces, and costs for intermediaries (project managers and project cargo forwarders). Storage providers make warehouses, yards, and storage areas available for storage of transportation equipment, wind turbine parts, components, and modules. Rail operators provide specialized rail transport for these parts and components. Specialty trucks along with land-based cranes are required to move modules such as blades and nacelles, for example, from the place of manufacturing or assembly to the site location. Freight forwarders (project forwarders) “glue together” a number of supply chain processes and take responsibility for service quality, safety, and supply chain hand-offs. The parts are also sourced from various locations globally into the assembly plant. In a series of interviews conducted by researchers at Aalborg University in Denmark (Poulsen et al., 2013), respondents stated that the complexity of the wind power supply chain, when coupled with internal departmental fragmentation as often seen in utilities companies, creates a “silo-based” approach to supply chain costs. This results in a reduction in clarity of the overall supply chain picture, blurring our ability to create an industry average cost of the end-to-end shipping, logistics, and supply chain process costs. Linking modes of transport across multi-modal supply chains on a global basis is a complex undertaking which requires significant investments in facilities, transportation equipment, people, IT systems, and knowledge management (Christopher, 2010).

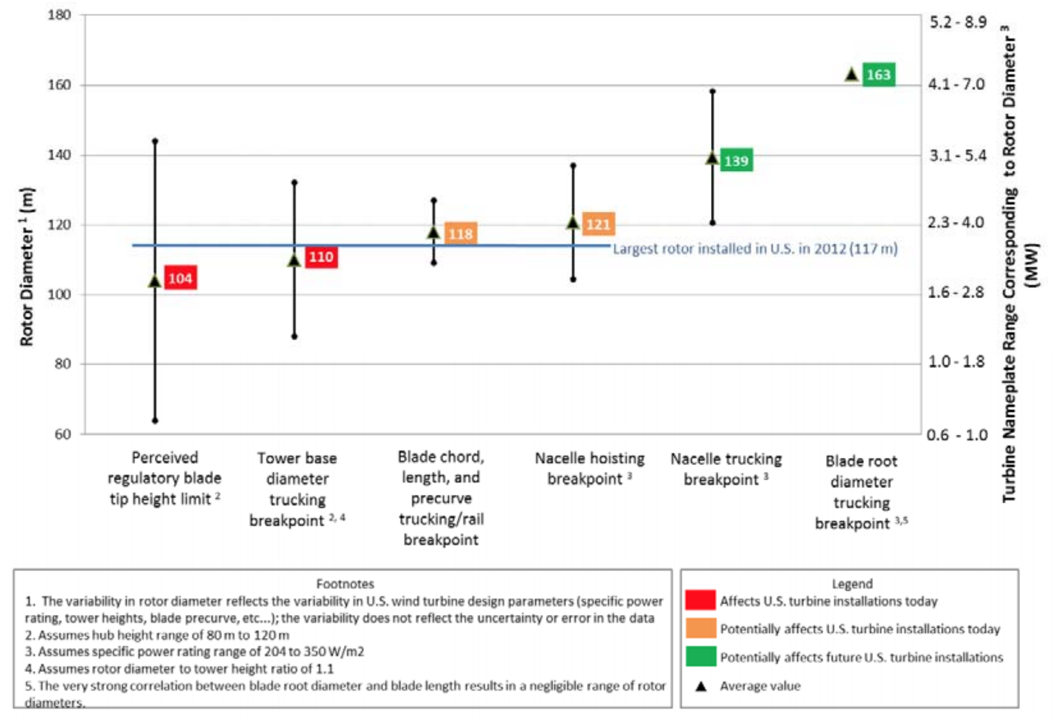
4.15 Additive Manufacturing to Address Logistics

When looking at the logistical supply chain drivers, we would like target certain areas of focus that we feel could be best improved/altered by the implementation of additive manufacturing. Within facilities, we hope to achieve greater flexibility in production through AM implementation. Within inventories, we hope to reduce work-in-process parts and final product inventory levels, placing greater focus on the raw material inputs used for AM. Within transportation, we hope to relieve traditional constraints present within each route/node relationship.

The US National Renewable Energy Laboratory has identified a series of “breakpoints” that create bottlenecks in the development of larger, more powerful turbines in the US. A breakpoint can be defined as the point at which transportation and logistics costs begin to increase more rapidly with the size of the wind turbine. They have broken down these breakpoints into the following categories:

1. Affects US installations today:
    a. Perceived regulatory blade tip height limit is 152m which corresponds to turbines ~1.7MW to ~3MW
    b. Tower base diameter trucking breakpoint is ~4.3m which affects towers 80m to 160m and turbines larger than ~1.9MW
2. Potentially affects US installations today:

   a. Blade chord length (blade width), length, and precurve dimensions constrain trucking and rail to ~53m to ~62m long blades, which corresponds to turbines ~2.2MW to ~3.8MW
   b. Nacelle hoisting breakpoint is ~120m hub height for a 3MW turbine
3. Potentially affects future US installations:
   a. Nacelle trucking breakpoint for a conventional nacelle is ~100 metric tons with the drivetrain removed which corresponds to a turbine of ~4MW
   b. Blade root diameter trucking breakpoint is ~4.3m which corresponds to ~80m blades and turbines ~4.3MW to ~7.3MW



Footnotes

1. The variability in rotor diameter reflects the variability in U.S. wind turbine design parameters (specific power rating, tower heights, blade precurve, etc...); the variability does not reflect the uncertainty or error in the data
2. Assumes hub height range of 80 m to 120 m
3. Assumes specific power rating range of 204 to 350 W/m2
4. Assumes rotor diameter to tower height ratio of 1.1
5. The very strong correlation between blade root diameter and blade length results in a negligible range of rotor diameters.

Figure 28: Turbine Supply Chain Breakpoints, Source: NREL

Technologies that enable larger wind turbines on taller towers create opportunities to further reduce the LCOE of wind farms. However, transportation and logistics challenges limit the size and tower height of land-based turbines that can be deployed in the United States (Cotrell et al., 2014). The blade transportation challenge is caused by the difficulty of transporting long, wide blades around turns, through narrow passages, and beneath overhead obstructions on US roads and railways (2a). Tower sections are generally limited to 4.3m in diameter, or, in some cases, 4.6m if routes permit, to fit under overhead obstructions (1b). The US Department of Energy is currently exploring programs to promote innovation in wind turbine technologies to address these issues and breakpoints to promote the further development of advanced wind farms. Some of the innovative technologies being considered include segmented blades and on-site tower manufacturing. However, they state that continued or expanded financial support for low technology readiness level technologies, which are often developed by small and midsize companies will help bridge the gap to commercialization of these technologies by larger companies with more substantial resources. Additive manufacturing helps bridge this gap, promoting more localized manufacturing, aiding in the development of segmented design, and breaking down the barriers associated with the transportation issues and breakpoints discussed earlier. The following image outlines the potential future outlook if technologies such as additive manufacturing can be successfully applied to address the logistical challenges currently being faced by the industry.

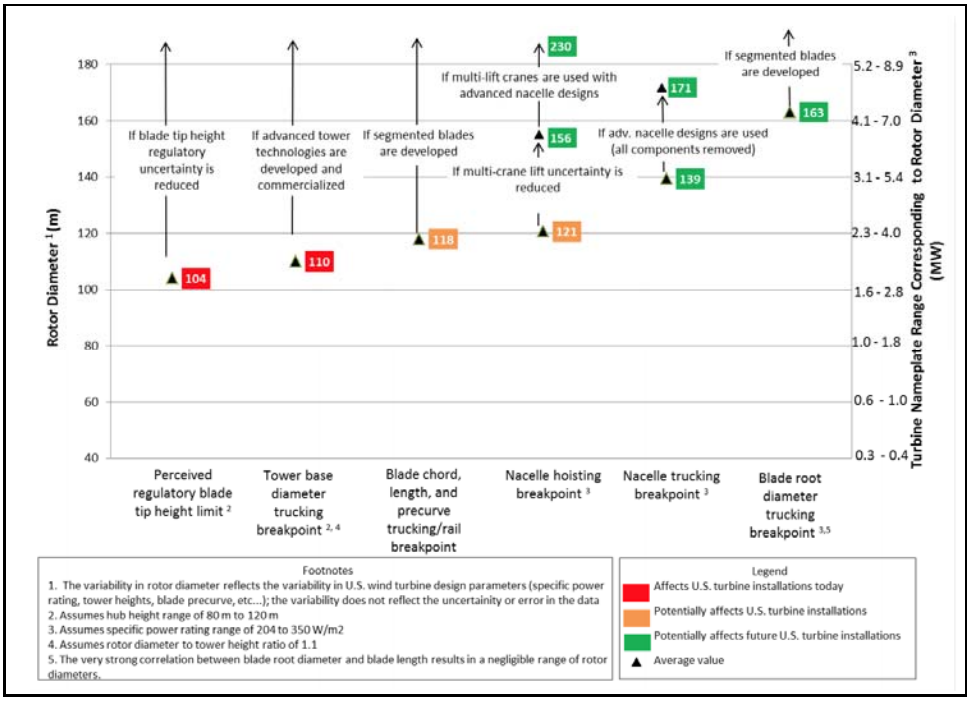


Figure 29: Future Outlook of Turbine Supply Chain Breakpoints, Source: NREL

5. Methodology

The data collection process for this research was a combination of primary and secondary data. Primary data was sourced through one-on-one contact with a variety of professionals and experts from both the wind energy industry, as well as the additive manufacturing space. To form our understanding of both of these industries we solicited numerous phone calls, and exchanged many emails with industry experts. Our experts were sourced as a combination of wind power engineers, turbine manufacturing sales staff, additive manufacturing sales staff, wind energy research scientists, energy industry consultants, and additive manufacturing consultants. By utilizing the knowledge these individuals provided, we were able to get a clearer picture of the potential that additive manufacturing has to innovate the wind power industry. Along with this extensive series of interviews, we also collected secondary data. Secondary data sources include a variety of existing research papers on both wind energy and additive manufacturing, as well as quantitative data from US government-sponsored initiatives such as the National Renewable Energy Laboratory, the American Wind Energy Association, and the US Energy Information Administration.

The collection of primary data from additive manufacturing machinery suppliers was straightforward, as information is quite public, and figures such as build speeds, build volumes, material costs, and printing unit capital costs are widely available. However, through our data collection process, we discovered that it was a difficult task to get primary quantitative data from either wind turbine manufacturers or suppliers. Many of these cost figures were viewed as “trade secrets”, and cooperating organizations were not willing to share this type of data to assist in our research (Smith, 2014). For this reason, we decided to reach out of the Oak Ridge National Laboratory (ORNL), a science and technology national laboratory managed for the United States Department of Energy. We were able to leverage data provided from ORNL about wind turbine manufacturing costs, both in conventional processes, as well as through additive manufacturing, including production times, material costs, facilities costs, and a variety of other metrics. The data has been collected through a project based on a partnership of the US Department of Energy’s (DOE) Oak Ridge National Laboratory (ORNL), National Renewable Energy Laboratory (NREL), Sandia National Laboratories, and private company TPI Composites, with the goal of demonstrating the significant time and cost savings potential of using additive manufacturing techniques in the construction of wind turbine blades.

The data on additively manufactured wind turbine blade molds was developed through an actual production of a demonstrative set of 13-meter molds by the ORNL. These molds were further used to produce a set of 3 blades for use on a wind turbine. While this size of blade is not of current industrial electricity production standards the data gathered is able to be utilized and applied through extrapolation. The extrapolation of data is not so much based on merely the multiples of blade length as one might initially think but rather of blade surface area.

The end goal of our data collection process was to first be able to understand the steps taken to manufacturing a utility scale wind turbine. Next, we needed to identify the cost of manufacturing a wind turbine using traditional methods, and allocate the costs across the different turbine components. After this, we needed to isolate certain components, and give a well-founded assumption as to their potential for additive manufacturing. Once we had a list of components, we then selected the component that we felt was most suitable for additive manufacturing, and represented a large enough cost share of the overall turbine that a reduction in manufacturing cost would have a large enough overall impact on the LCOE of wind energy generation for the whole turbine - the part we selected was the turbine blade. After the blade was selected, we investigated the best way to couple additive manufacturing with the blade fabrication process to lower overall costs. Gebler et al.'s article highlighting breakeven points for additive manufacturing as compared to conventional manufacturing makes it clear that the production numbers of wind turbine blades from any one company (in the hundreds or thousands) is in excess the breakeven advantageous point of additive manufacturing since blades are usually produced in the hundreds if not thousands. This would make the cost of additively manufacturing blades higher than through traditional manufacturing. In addition to this there are technical limitations to printing an entire blade in current utility scale sizes as a whole piece such as the current maximum print size and there has been no research or experiments on printing blades and without this technical understanding or knowledge from engineers it is difficult to state whether this is feasible with current technologies. At this point, we determined that by manufacturing the blade mold which is used to form the turbine blade using additive manufacturing, we could eliminate one step of the process entirely (the creation of the blade plug), and have the potential to also reduce the cost of the mold, with additional benefits including better product customization and a reduction in mold switching costs. The final step of the process was to break apart the cost of the traditional blade manufacturing process, as well as the process using additive manufacturing to produce the molds using our build speeds and build volumes provided by manufacturers of additive machinery. We were then able to create a “per unit cost” for each blade in both scenarios, apply this to the overall cost of a wind turbine, and quantify a theoretical cost reduction in a percentage of total turbine cost figure. Once we had these two blade costs, we could plug them back into the LCOE equation (Eq. 2), and derive an overall reduction rate of the LCOE.

6. Model

6.1 The Current State of Wind Turbine Blade Mold Production

The creation of a modern wind turbine blade begins with the creation of what is called a plug or master mold. The purpose of the plug is to create a full-size representation of the final blade. This plug is created using polystyrene foam blanks in 6-8 meter pieces which can be joined together. The blanks are first machined to their approximate size. A machining paste is then applied to the plug or it is over laminated (although this may result in lower quality). The plug is then machined using a computer numerical control (CNC) machine to the exact desired shape. The plug is then sanded and polished to a smooth finish. The mold is then made from the plug which is an inverse of the plug representation. The mold is 2 halves or "shells" of the plug and is typically made of fiberglass and requires a heating element be installed so the mold to take its shape and reach proper cure temperatures. A plug can produce between 6-10 mold sets before it must be refinished or a new plug must be made. Once the mold has been pulled from the plug its surface is refinished. The molds surface quality and accuracy is extremely important as the quality of the mold will directly influence the quality of blades produced. Once the mold has been created other features such as a steel frame and heating wires are installed (Marsh, 2007). Due to the uniqueness of each plug and mold a large majority of the process is not automated and therefore requires extensive labour.

Once the mold has been created, blades can be manufactured using the mold. Blades are created by laying sheets of fiberglass inside of the mold shells. The two mold halves are then joined together and the mold is then heated to a temperature of 50-120 degrees (depending on fiberglass process; infusion or prepreg) and a vacuum is applied to withdraw excess air. A 35-meter blade typically takes between 19 and 23 hours of the molds time depending on the level of automation as well as the type of material or fiberglass technology utilized - infusion vs prepreg (Gurit, 2012). After the molding process is complete the blade must still go through a finishing process to bring the blade to a complete smooth finish. There are many trade-offs between levels of automation and fiberglass technology such as equipment costs, labour costs, material costs, facility size, production time and finished blade quality. While processes for manufacturing blades can vary, the tools - plugs and molds largely remain made of the same materials and produced using the same processes. A mold is typically capable of producing between 600-1000 blades before they need to be refinished. While blade molds are capable of producing potentially several thousand blades they rarely ever reach this level since blade design and length are constantly changing to increase the blades efficiency and power making the mold obsolete (Marsh, 2007).

Supply chain processes for plug and mold production are challenging and time consuming. A typical 50-meter plug takes approximately 12 weeks to produce. Once this is completed, the mold production and assembly can take place. Mold production and assembly takes approximately 15 weeks from beginning to end using about 9 weeks of the plugs time. Therefore, a new mold can be produced with the same plug every 9 weeks (ORNL, 2016). Transportation of the plug and or mold may also add additional time to the process particularly when manufacturing sites are not near each other. Additionally, the transportation of plugs and molds can be both challenging and expensive due to size.

Wind turbine blade & turbine producers have a variety of ways of acquiring molds; some producers produce the mold in-house and others purchase the mold from a tooling company. While it is difficult to know for certain it seems likely that no blade manufacturer's manufacture their own plugs as even a larger blade manufacturer LM Wind (owned by General Electric) does not produce their own plugs. Gurit, a composite materials company based in Switzerland and has manufacturing facilities globally, claims to be the largest provider of blade molds.

Figure 30 (left): Finished mold being transported. Figure 31 (right): Finished mold, Source: Marsh 2007

6.2 Proposed Turbine Blade Production Method Utilizing Additive Manufacturing

Unlike traditional manufacturing where a plug is required for mold production, additive manufacturing enables direct manufacturing of the mold, skipping the requirement to produce a plug. The first step in the process of creating a turbine blade via additive manufacturing is the creation of the computerized object model of the mold, which is sliced up by a printer into tool patterns the printer can follow to print the mold. The current capacity of even the largest commercially available machine today is not large enough to print an entire mold as one piece, therefore, the prints are broken into sizes that are manageable by the machine. To print each section a build sheet is put down in the printing area and the machine is loaded with the required amount of print material and the material is heated for 2 hours. The material used in the machine for the molds in the demonstrative molds was ABS material loaded with 20% carbon fibre. The carbon fibre is added to increase the strength, stiffness, thermal conductivity (which is important for blade production), and reduce the coefficient of thermal expansion to avoid warping of the material (Love & Post, PC 2017).

The sections of the print are then printed, one at a time. Print speeds can vary somewhat based on the design that is printed. For the mold in question being printed, the printer prints at an average rate of 36.4 kg/h of material taking an average of 34 hours to print each section. The sections are grown to the final required size of the mold less 4 mm on the mold surface area. It then takes approximately 2 hours to remove each section and clean the machine, then the process can be started over again with a new section. In total, a 50-meter blade would require 60 different sections to be printed. (Love & Post, PC 2017)

After each section is finished printing, it is coated with a 8 mm layer of fiberglass then machined down 4 mm in order to meet the tolerance quality standards for blade production. In the demonstrative molds this was done with 2 printed sections at a time.

The final steps are to then install the heating components and assemble the sections together utilizing an egg crate steel structure. The purpose of the egg crate steel structure is to provide additional stability to the mold as well to be used for hoisting the mold during blade production (Love & Post, PC 2017). Finally, the surface of the mold is finished with a sealant and the mold goes through a quality assurance check before it is utilized for blade manufacturing.

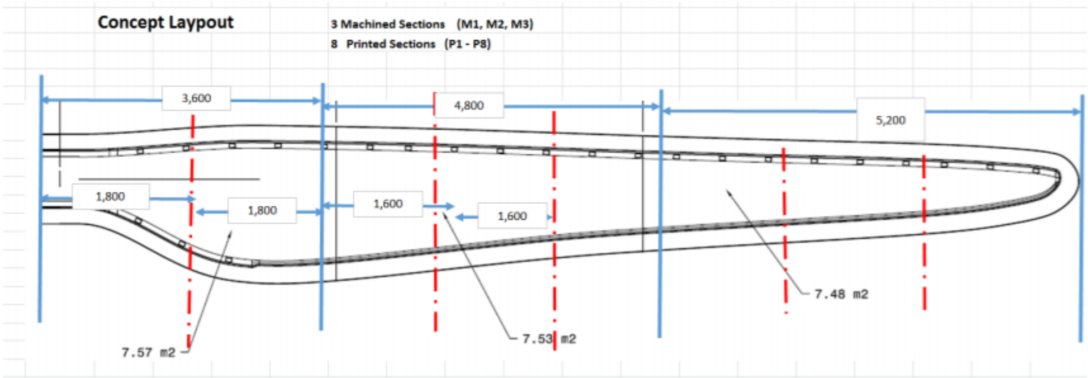


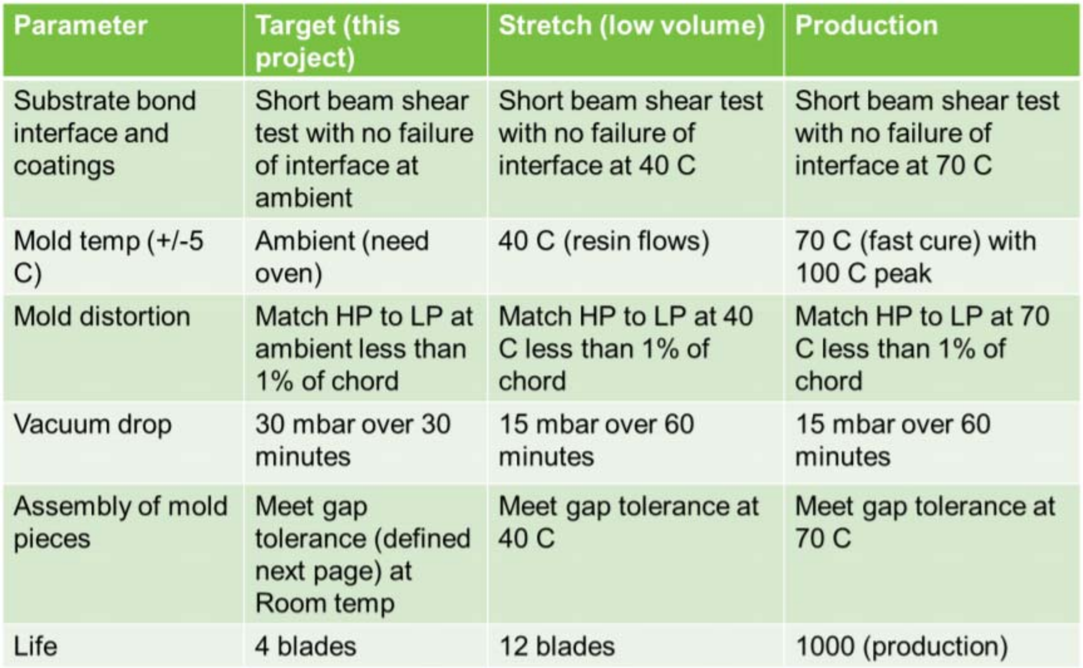
Figure 32: Illustration of blade mold cut into manageable printing sections, Source: ORNL

Figure 33: Additively manufactured molds ready for use, Source: ORNL

Figure 34: Process for AM blades, Source: ORNL

6.3 Technical Feasibility Assessment of AM Molds

Based on discussions with those at ORNL, there were certain technical specifications (parameters) that the mold needed to have in order to be utilized in mass blade production. Based on the evaluation of the demonstrative mold produced by the ORNL then utilized for blade manufacturing by its partner TPI Composites the mold has met all of the parameters required for production (figure 35).



Parameter	Target (this project)	Stretch (low volume)	Production
Substrate bond interface and coatings	Short beam shear test with no failure of interface at ambient	Short beam shear test with no failure of interface at 40 C	Short beam shear test with no failure of interface at 70 C
Mold temp (+/-5 C)	Ambient (need oven)	40 C (resin flows)	70 C (fast cure) with 100 C peak
Mold distortion	Match HP to LP at ambient less than 1% of chord	Match HP to LP at 40 C less than 1% of chord	Match HP to LP at 70 C less than 1% of chord
Vacuum drop	30 mbar over 30 minutes	15 mbar over 60 minutes	15 mbar over 60 minutes
Assembly of mold pieces	Meet gap tolerance (defined next page) at Room temp	Meet gap tolerance at 40 C	Meet gap tolerance at 70 C
Life	4 blades	12 blades	1000 (production)

Figure 35: Technical parameters of a wind turbine blade mold, Source: TPI Composites

7. Analysis

7.1 Cost to Produce a Blade Mold Using Conventional Manufacturing

The cost to produce a wind turbine mold is considered confidential material and a competitive advantage to mold producers, therefore acquiring such a cost and validating its accuracy proved very difficult. Based on the cost curve provided by Wiley (2010) we have estimated the cost to produce a 50-meter blade to be in the area of $2 500 000, which we have further validated through our discussions with contacts at the Oak Ridge National Laboratory. It is, however, important to note that these costs are likely to vary based on location of manufacturing due to labour and material costs as well as the overall quality of finished mold. Plugs or master molds can be used to manufacture 6 - 10 molds, and therefore it is assumed that the depreciated cost of the plug is allocated across 8 molds.

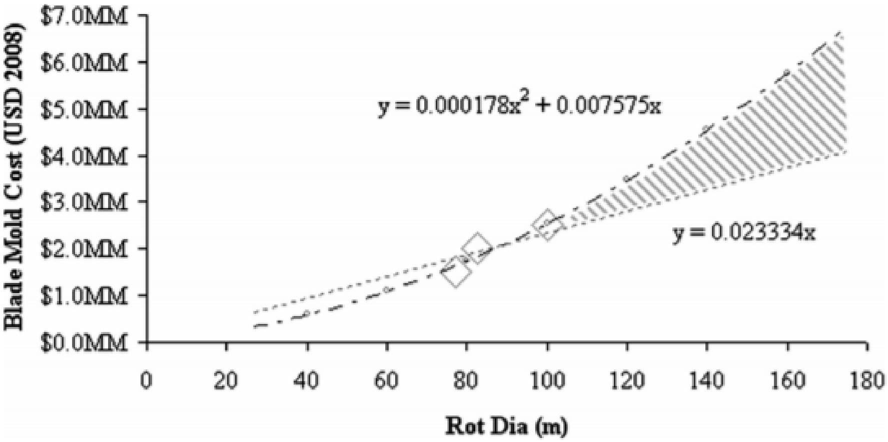


Figure 36: Cost curve of blade molds as a function of rotor diameter, Source: Willey, 2010

<u>Note on Plug Cost:</u>

It has been assumed that a portion of the plug cost has been allocated to each mold so that when all molds are produced the plug is fully depreciated

(ie: $1 million plug divided by 5 molds = $200,000 allocated).

7.2 Cost to Produce a Mold through Additive Manufacturing

Since data was publicly available and shared by the US Department of Energy & Oak Ridge National Laboratory a clear establishment of costs and cost drivers were easily identified. For a list of assumptions used see Appendix A.

Materials

- Materials include printer material, build sheets for prints, a heating system to be installed into the mold, and a egg crate steel frame for the printed sections to be assembled within.

Printer Time

- Depreciation of the machine is allocated to every build based on number of hours the printer is used for each print job, divided by the total usable hours, which is based on budgeted utilization rates

Machining Costs

- A cost-per-hour of the machine depreciation, or to alternatively take the molds to a machining shop and have the process subcontracted

Finishing

- The cost for final sealant applied to the mold surface as well any further manual touch ups that must be done to have the blade mold surface in ready-to-use condition

Direct Labour

- Cost is made up of 3 components; This is the cost for the designer to build the computerized design to be executed by the machine, for the supervisory time of monitoring the printing machine, and for the final assembly of the sections and installation of the heating system

Overhead

- These indirect costs associated with mold production manufacturing can be separated into areas such as building deprecation & maintenance, electricity, plant supervisor, maintenance, shipping and receiving personal. Overhead is charged on a basis of area of use and standardized hourly rates.

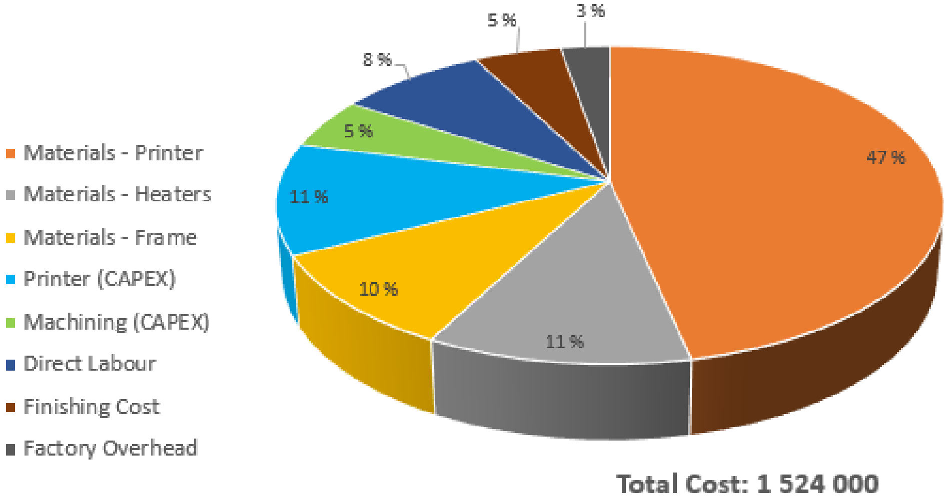


Figure 37: Cost breakdown of additively manufactured wind turbine mold, Created by Authors

7.3 Comparison of LCOE

To calculate the LCOE (Levelized Cost of Electricity) comparison between the traditional mold production method and the proposed new method of additively manufacturing we have configured a cost allocation to each blade and then to the whole turbine using the total cost to produce each blade considering the cost allocation of the mold.

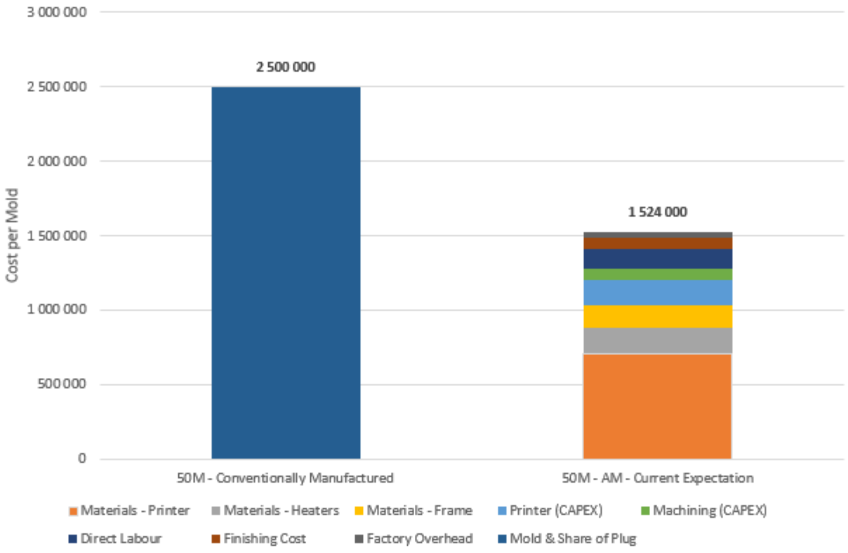


Figure 38: Comparison of conventional and additively manufactured mold costs, Created by Authors

The calculation of the mold cost per blade produced is fairly simple and can be calculated by:

Eq. 5: Total Mold Cost / Total Number of Blades Produced

A low number of blades might be produced from a mold in some instances such as prototype blades or built specifically for a wind site. Figure 39 highlights that the mold cost per blade is significant for the first approximately 150 blades but normalizes after on, however it is clear that no matter what the number of blades produced is, the lower cost additively manufactured mold offers cost savings.

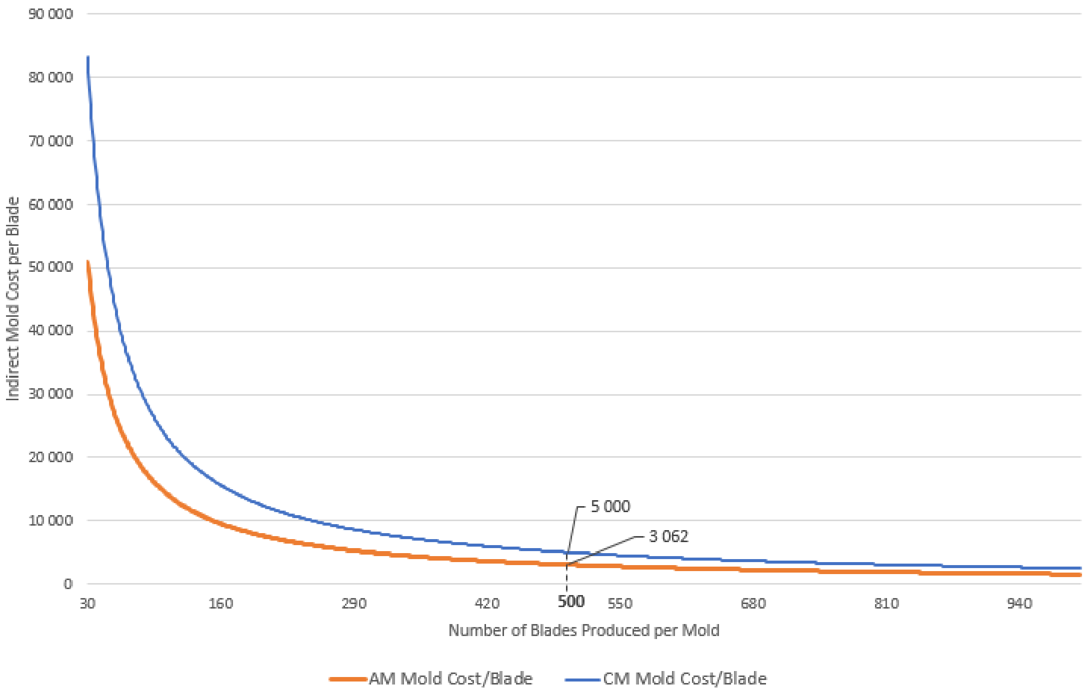


Figure 39: Cost of mold allocated to each blade under each manufacturing method dependant on number of blades produced from the mold, Created by Authors.

To calculate the LCOE changes we have calculated the LCOE based on a standardized average wind turbine farm with the following specifications based on NREL’s 2015 Cost of Wind Energy Review (Mone et al., 2017) focused mainly on the continental United States. This was done since it is it is based on recent wind turbine farm installations and because we had contacts from within the NREL and could therefore develop a better understanding of the assumptions.

The main LCOE specifications are as follows (Appendix B gives further details into the inputs):

CapEx (including installation): $3 338 000

FCR (Fixed charge rate): 9,6%

OpEx (Annual operating expenses): $102 000

AEP net (Net average annual energy production): 6 990 Megawatt hours

Operational life: 20 years

If we then assume that the average blade mold is utilized to produce 500 blades then we can calculate the difference between the total turbine costs under each method of production by only changing these variables then placing the capex cost back into the LCOE formula.

*Eq. 6: CapEx; Conventional Manufacturing = Tc + ($2 500 000/X) - ($5 000*3);*

*Eq. 7: CapEx: Additive Manufacturing = Tc + ($1 524 000/X) - ($5 000*3);*

Where:

- Tc is the turbine capital cost
- X is the number of blades produced using the mold
- $2 500 000 is the cost of the conventional mold
- $1 524 000 is the cost of the additively manufactured mold
- $5 000 is the mold cost per blade when 500 blades are produced using a conventional mold ($2 500 000 / 500 = $5 000)
- 3 blades are used in each wind turbine

LCOE formula for wind energy (from eq. 2):

$$\text{LCOE} = \frac{(\text{CapEx} \times \text{FCR}) + \text{OpEx}}{(\text{AEP}_{\text{net}}/1{,}000)}$$

Based on this assumption of 500 blades of production from the mold, the LCOE of a wind turbine produced through the traditional method would have an LCOE of $61,01 USD and an LCOE through the additive mold manufacturing method of $60,93 resulting in a cost savings $0,08 per MWh (Megawatt hour).

We can further extrapolate this comparison to examine what effect producing more or less blades with each mold would result in under each type of mold production (Figure 40).

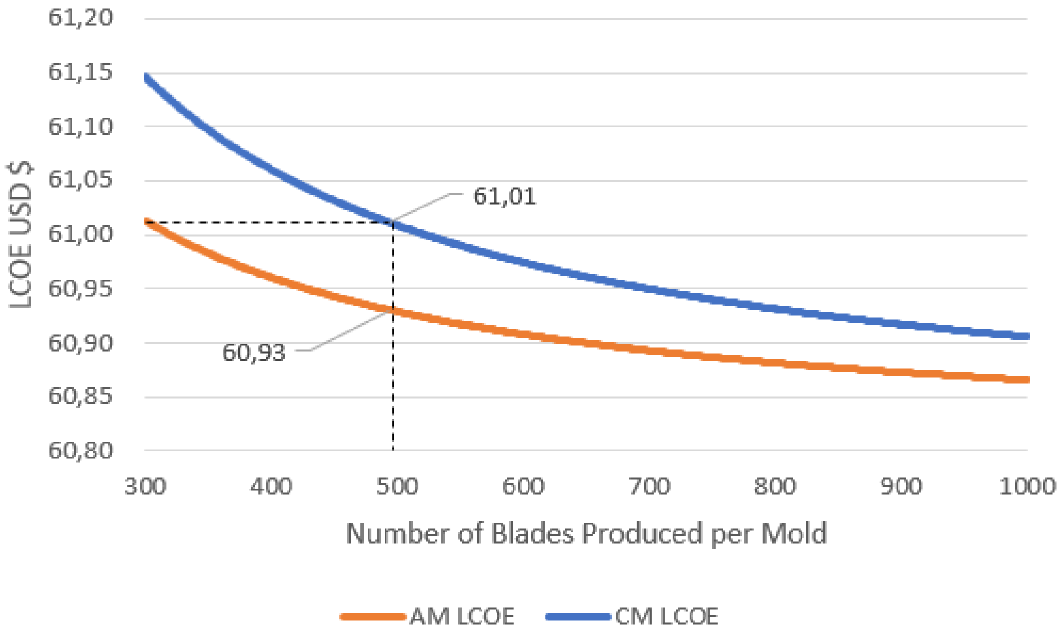


Figure 40: Mold Production Volume Effects on LCOE (Levelized Cost of Energy), Created by Authors.

As the number of blades produced per mold increases, the cost benefits of the additively manufactured mold become smaller. Conversely, the as the number of blades produced per mold decreases, the cost benefits of the additively manufactured mold become larger and therefore a greater benefit will be realized in cases where blade molds are utilized for lower production runs.

7.4 Potential Further Cost Changes

Based on current technology and methodology, the theoretical cost advantage of producing a wind turbine blade through additive manufacturing is only marginally advantageous to the conventional technique used in today's production. Future research and experimentation may, in fact, reveal further cost benefits such as a change in printing material or density/volume of the final print. Based on our knowledge of additive manufacturing and specific discussions with the demonstrative mold project leaders; a number of alternative scenarios have been hypothesized and the 50M turbine blade cost has been recalculated and compared to our current projected costs:

7.4.1 Mold Design Optimization

In case of the event that print volume must increase, due to the production demands requiring additional stiffness and durability for the production process, the amount of material would increase as would the number of hours on the print machine and therefore the labour and overhead associated with it. Conversely, the current belief of the project leads is that the demo 13-meter blade mold (and therefore the 50-meter mold projections) was overbuilt and likely could go through further optimization to utilize less materials therefore resulting in reduced material use, reduced printing time, reduced overhead time allocated, and reduced labour costs associated with the printer. This attribute has identified as the strongest cost driver for the mold cost due the large cost portion materials makes up of the mold as well as the influence the optimization of the print has on the other costs.

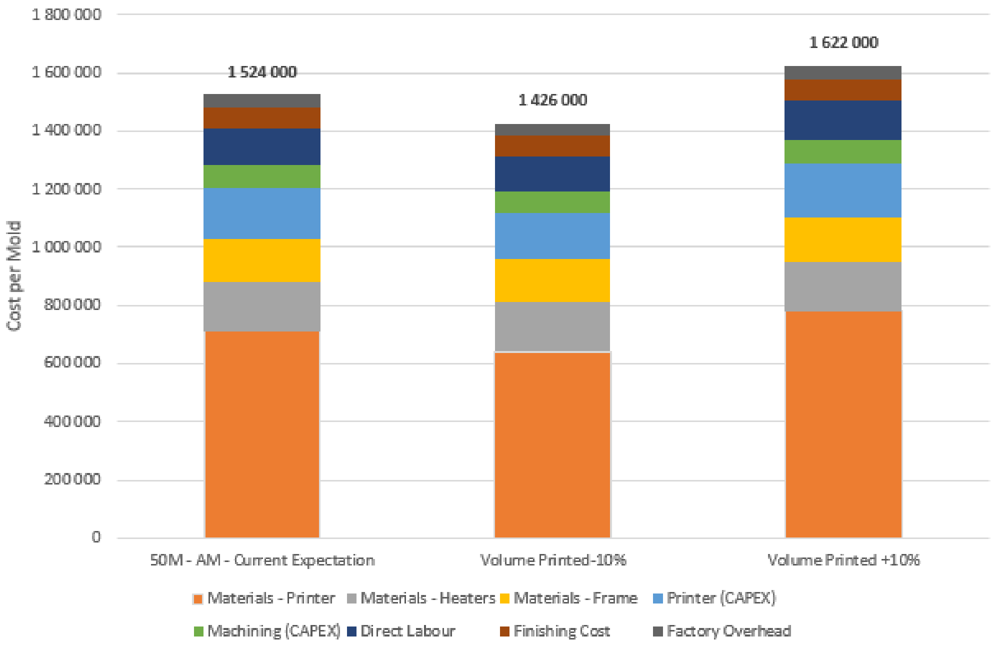


Figure 41: Comparison of mold costs based on changes in print volume, Created by Authors.

7.4.2 Material Cost

Material costs make up a significant balance of the mold cost and efforts to utilize different materials or material mixes could lead to lower material cost per mold produced. In the demonstration mold and in the extrapolated 50M mold the price per kilogram of material is $9,55 USD. However, it is likely that through higher purchase volume a lower price could be achieved or alternatively and or combined with it may be possible to utilize another material than currently used ABS with 20% carbon that would result in lower materials cost. It is also possible that the price of material may increase due to a needed change for mold durability and or other effect other technical parameters such as thermal conductivity which if increased could increase the molds productivity.

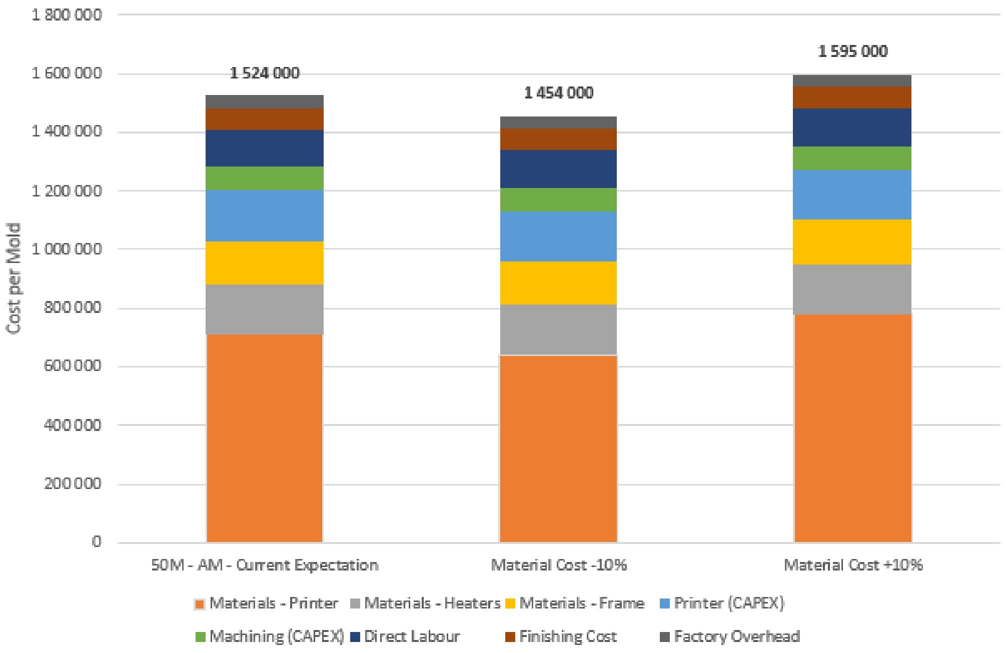


Figure 42: Comparison of mold costs based on changes in material cost, Created by Authors.

7.4.3 Printing Speed

An increase in printing speed could drastically influence the attractiveness of additive manufacturing over conventional manufacturing. Faster printing speeds would result in faster production time and therefore sooner use of mold for production purposes. Faster production time would also likely result in lower costs as the machine is used for less time on each print and a supervisor managing the printing process would not be needed for as many hours; this is assuming that the capital purchase cost of the printer and the utilization of the printer would not change as a result. Based on current market trends and new developments a printer such as the Ingersoll Machine Tool Company's Wide High Additive Manufacturing (WHAM) with the capability of printing 10 times this amount per hour (approximately 450 kg/hour maximum). Unfortunately, more advanced additive manufacturing machines such as this will cost more and currently are estimated to cost approximately 11M USD in the near-term future. However, the machine that was utilized to print the 13-meter molds and then forecasted for the 50-meter mold has a max print speed of

45 kg/h but only printed the mold at a rate of 36,4 kg/h. Therefore, the current technological state already allows a faster printing speed if the print builds can be further optimized.

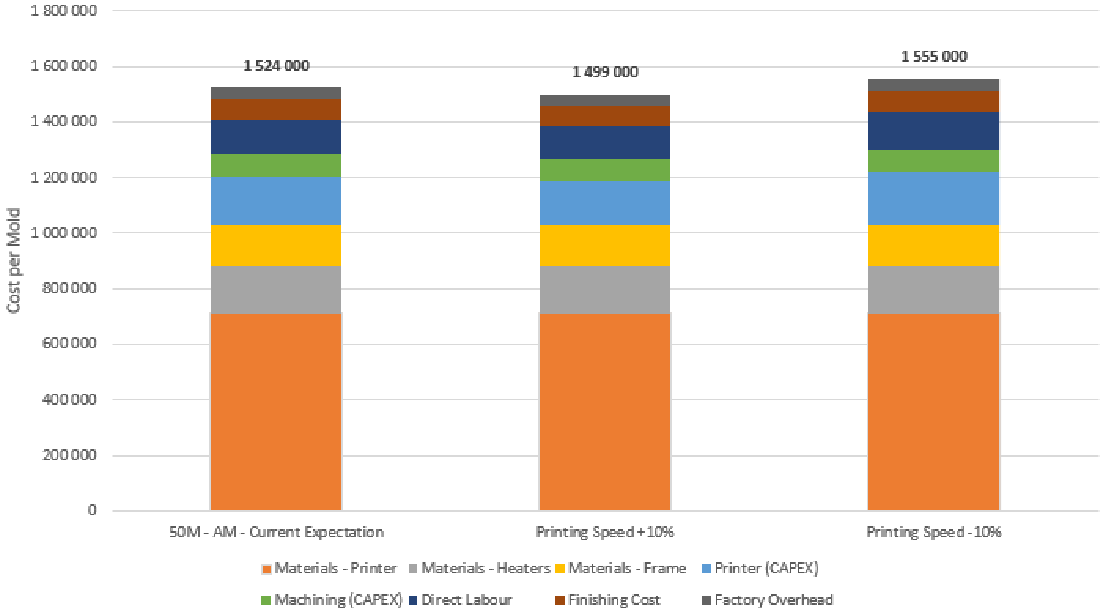


Figure 43: Comparison of mold costs based on changes in printer speeds, Created by Authors.

7.4.4 Printing Size

The additive manufacturing machine utilized for the production of the demonstrative 13 meter blades and then utilized in the forecast of 50-meter blade costs was Cincinnati Incorporated's BAAM with a max build size of 610 X 229 X 183 CM. This size constraint requires that for a 50-meter blade mold to be produced, it must be produced in 60 separate prints that can later be adjoined. As the additive manufacturing technology develops, new printers such as the Ingersoll Machine Tool company's' Wide High Additive Manufacturing (WHAM) with a max build size of approximately 7,5 X 6 X 30 meters. This would reduce the printer downtime between print jobs as well as reduce the labour requirement for final assembly. Unfortunately, more advanced additive manufacturing machines such as this will cost more and currently are estimated to cost approximately 11M USD in the near-term future.

7.4.5 Printer Utilization

The utilization of the printer is extremely important to get the most value of the capital purchase cost. In the simulation cost of a 50-meter blade mold production the utilization of the printer is estimated at 50% meaning that it is utilized 50% of all available hours of the year. This would translate into approximately 2 sets of 50-meter blade molds produced each year. If we are to assume full printer utilization which is estimated at 90% of all hours of the year to allow for downtime due to maintenance the hourly capital cost of the machine would drop significantly. Alternatively, if the printer is underutilized and is only seldom used for mold production such as for experimental blade designs and is only utilized at 25% - the equivalent of 1 set of 50-meter blade molds, then the cost allocation of this resource increases significantly.

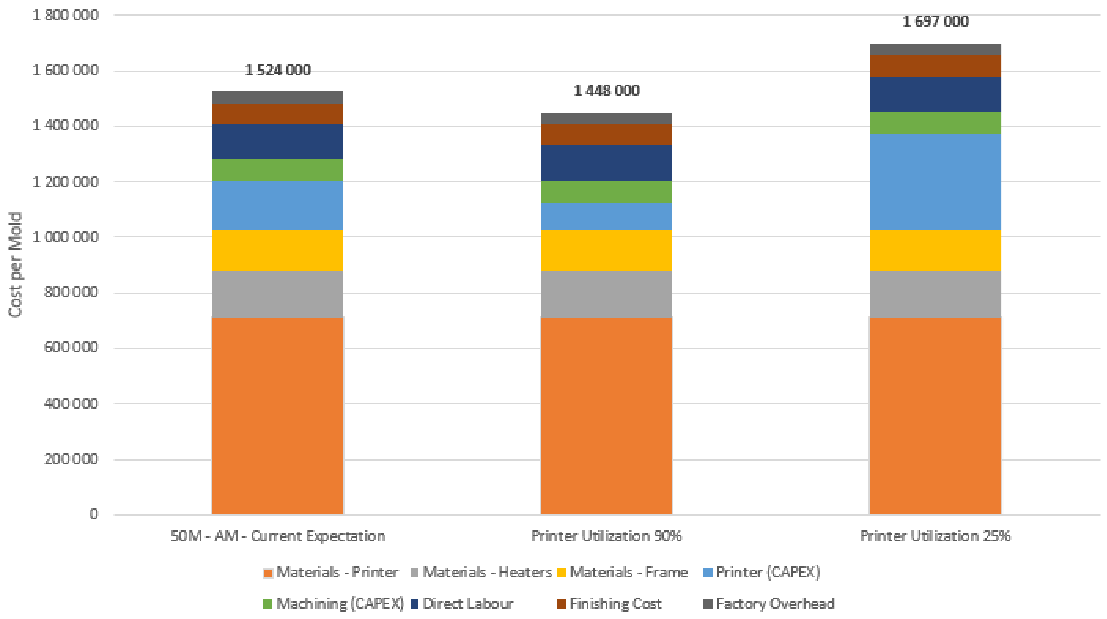


Figure 44: Comparison of mold costs based on changes in printer utilization, Created by Authors.

7.4.6 Elimination of Fiberglass Surfacing

The cost of the fiberglass surfacing of 8mm that is then machined down 4mm to create a smooth finish before the final finishing process is very minimal, however it is likely that this step could be eliminated and the print material could be overgrown then machined down (L. Love, B. Post, PC 2017). While this would not result in notable cost savings it would reduce a step in the process and reduce production complexity.

7.5 Summary of Quantitative Analysis

The financial comparison between both methods of mold production it is evident that the additively manufactured mold is significantly cheaper than the traditionally produced mold. The cost savings at low levels of blade production per blade are very evident, whereas, with higher levels of production the cost savings per blade become less apparent. However, it is clear that no matter what level of blade production is done with a blade mold that the additively manufactured mold results in cost savings.

Furthermore, the analysis and discussion of future cost changes it seems likely that the cost to produce the mold through additive manufacture will decrease as the technology develops and as producers find methods of optimizing the process.

7.6 Qualitative Evaluation: Advantages/Opportunities

7.6.1 Production Time

The production process of a mold through additive manufacturing is faster than through the conventional manufacturing process. This is largely realized through skipping the plug manufacturing step in conventional manufacturing. The total production time through the traditional method and additively manufactured method is 27 weeks and 20 weeks respectively. Therefore, the additively manufactured blade mold has a shorter time to blade production by 7 weeks. In a theoretical blade production environment where production of blades begins immediately upon mold completion, the additively manufactured blade gains 7 weeks of productivity for the first mold, but only 4 weeks for the second mold, however then falls behind the traditional approach upon completion of the 4th mold by 1 week and continues to fall behind after. This is due to the long timeline of plug production in the traditional approach which does not have to be done to make the second mold and beyond, therefore it should be noted that there is a production time trade-off based on number of molds produced. This is due to the bottleneck of the time spent with the printer to produce the mold is 12 weeks (assuming only 1 BAAM machine is utilized) and the time spent with the plug to produce the mold under the traditional approach is 9 weeks. It should be noted that the additional 7 weeks gained on the first mold and following 4 weeks gained on the second mold means that it is not until completion of the 6th conventionally manufactured mold that the additively manufactured process falls behind the conventionally used process for blade production purposes. A significant benefit to the blade manufacturer and the LCOE of wind energy is the ability to introduce better blade designs sooner.

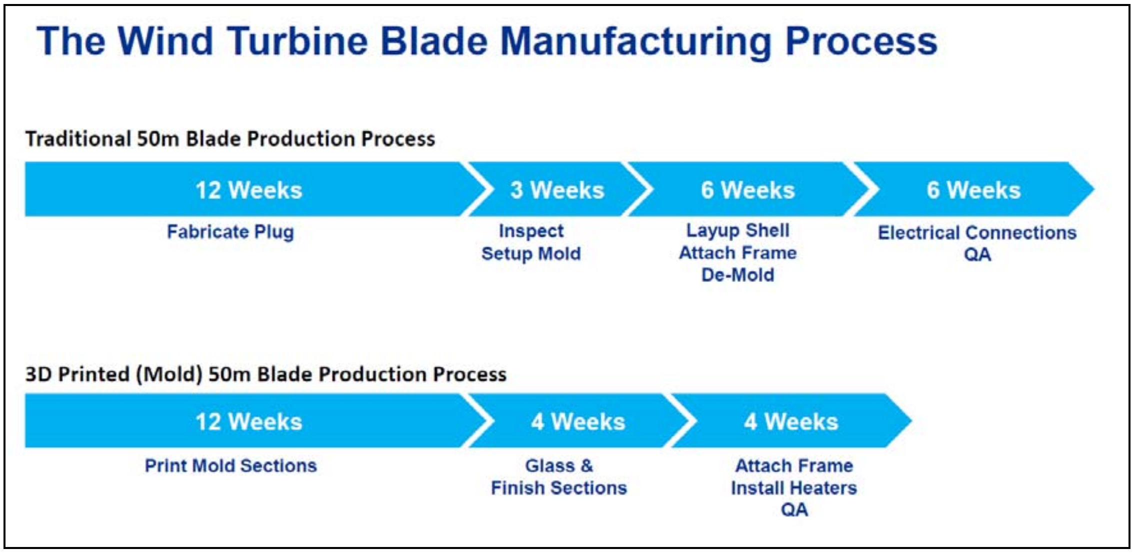


Figure 45: Conventional vs Additive Manufacturing Timeline, Created by Authors

7.6.2 Added Manufacturing Flexibility

Reduced requirement to produce multiple identical molds in effort to spread capital and logistical cost of a blade plug. This offers easier adjustments for blade manufacturers to local market conditions where blades can be fine-tuned to the environment they operate in.

7.6.3 Modularity

Since the mold is produced in sections, it is possible also to replace only certain sections with new replacements if they become damaged through use or transport or with updated designs in the event of new design innovations. This potential offers further cost savings to the mold cost offering blade manufacturers cost savings in producing a new mold and also time in producing a new section. This is a clearly sought after as General Electric - one of the largest turbine producers recently filed a patent on adding modularity to wind turbine molds by swapping sections (Hardwicke, Lin, & Rangarajan, 2017).

7.6.4 Easier Transport of Designs

Under current manufacturing methods, if a blade mold is designed and manufactured in one part of the world, it is possible to send the computer designs to another part very easily. However, because of the tied-up costs in the plug and multiple molds it may be more economical to ship these molds to another region rather than creating new ones from a new plug. Under additive manufacturing it would likely be simpler and cheaper to send the computer drawing then have it reprinted in the region of the world the design specifications are demanded.

7.6.5 On-Site Production

An identified advantage of utilizing additive manufacturing is that it may make it may make it possible to set up wind farms in previously unreachable regions due to infrastructure constraints. This would be done by assembling an additive manufacturing machine such as the CI BAAM on sight to produce molds, then blades at or nearby the wind turbine farm site. While there would be a significant cost of setting up such a production site many of these costs could be offset by significantly reduced transport costs and potentially high capacity factors from strong wind resources in certain regions.

7.6.6 Integration of Other Features into the Mold

The demonstrative molds integration of heating capabilities proved that features can be designed directly into the mold. This design feature reduces the amount of labour and allows for easy replacement in the case of faulty heating components in case of future breakdown. Other features such as systems for resin delivery into the mold for or sensors used in blade production could likely be designed and integrated into the printed mold shortening the process to prepare the mold for blade production. The result of these design integrations is a decrease manual tasks, labour hours and could potentially increase blade production efficiency. As highlighted previously, these integrated features are unlikely to change the mold cost significantly as with additive manufacturing – ‘complexity is free’

7.6.7 Reusable Heaters

The heaters that were installed into the additively manufactured mold can be easily removed and affixed to a new mold when the mold is out of date and disposed of or simply if the mold is not in use for a period of time. This reusability of components reduces the overall cost and simplifies the supply chain logistics.

7.6.8 Reusable Frame

The metal frame that is built can be utilized for future molds and can be manufactured to fit multiple designs and a variety of lengths. For example, a frame could be slightly overbuilt by making it slightly longer and wider than necessary but allowing it to be utilized for slightly larger or smaller mold/blade designs, this could be done by utilizing the design process to match printed sections to fit into the frame accordingly. This significantly relaxes the need to build custom frames for each mold and with it the corresponding supply chain demands to source more resources.

7.6.9 Recycling

Based on discussion with the project leads, the material that the mold is printed from can be recycled, however it is not clear at this time what the salvage value of this material would be in comparison with that of fiberglass.

7.6.10 Cost Savings

The reduced cost of each mold may influence and enable blade manufacturers to introduce more blade designs to the market than previously assuming the equivalent spending on capital investments (molds). This further encourages innovation and less generic one size or one design fits all blade manufacturing.

7.7 Qualitative Evaluation: Disadvantages/Challenges

Although the additively manufactured blade mold produces many advantages, there are still a number of areas that could propose a challenge by using this style of production. Some of those areas we have found would include:

7.7.1 New Technique of Manufacturing

Mold manufacturers will have to acquire the technical competence to work with additive manufacturing equipment. Additionally, while the trial experiment to produce a 13-meter blade mold was successful in producing one set of blades, the application to mass production of blades with commercial sizes may pose new technical challenges that have not yet been identified.

7.7.2 Change in Supply Chain

With the adoption of additive manufacturing, the supply chain for blade manufacturers will alter significantly. The overall nodes in the supply chain will decrease, and the overall time from design to market will be at an all-time low. However, this creates a few additional concerns for the manufacturer. The current state of the additive manufacturing industry is one in which companies who produce the machinery often restrict the type of raw material compatible with their product lines. This leaves the end users with very little options in terms of procurement of raw materials. Until the industry adopts a universal raw material feed, or increases compatibility across various platforms, it will be difficult for end user to achieve significant savings in raw materials simply due to the lack of availability of substitutes to their current suppliers. Additionally, capital costs are high for printing units due to the technology still being in its infancy. Companies may not be able to afford more than a single printing unit, and therefore cannot run multiple production lines simultaneously. If production needs are high, this creates a bottleneck in the system.

7.8 Summary of Qualitative Analysis

The qualitative analysis and discussion comparing the two methods of mold production reveal that the additively manufactured blade mold has many advantages over the traditional production method. The most beneficial benefits of the additively manufactured mold to the wind energy industry are faster production time, increased manufacturing flexibility allowing for further customization of designs and the enabling of on-site production enabling access to locations previously inaccessible.

While there are challenges to switching to this type of technology, the biggest is likely the sunk investments into current mold and blade manufacturing methods and developing the technical competences for the new method of production.

7.9 Potential Supply Chain Impacts

Currently, the mold manufacturing process of turbine blade construction is often subcontracted to tooling manufacturers such as Gurit - the largest supplier of blade molds globally, then purchased and utilized by the blade producers. The elimination of the plug eliminates a number of processes associated with the mold fabrication process, particularly those that are manual, labour intensive tasks. This removes a significant and cost-intensive barrier, and would more easily allow the turbine manufacturer to vertically integrate, and produce their own molds at self-owned facilities. This may result in cost savings benefits associated with margins, logistics, and a variety of other factors. The turbine producer would then own the entire design and manufacturing process, resulting in better control of delays, shorter time to market, better supply chain planning, and the protection of intellectual property related to the engineered design of the blade profile or manufacturing techniques useful. However, it is important to note that as attractive as this vertical integration may be, many businesses often don’t have adequate resources and capabilities to fully leverage this opportunity, whether it be a lack of space to take over production internally, a lack of skilled workers to design the parts and execute the printing processes, or a decentralized way of viewing the supply chain – an implied preference to outsourcing.

An example of such practice is Senvion’s purchase of EUROS Group specifically to acquire the mold making capacity and expertise of EUROS Group (Froese, 2016). Regarding the acquisition CEO of Senvion, Jergen Geissenger stated: "The EUROS transaction successfully builds on Senvion's product innovation and market entry strategy. With the addition of a mold factory and an experienced mold and blade development team, Senvion will be able to reach a shorter time to market for new blades and also be able to produce additional new blades with a reduced time to market. This will enable Senvion to enter new markets with new products more quickly. This strategic move is important to further prepare for our next market entries and also to achieve cost savings and thereby contributing to lower LCOE efforts."

8. Areas for Further Research

Mold Quality

The demonstrative molds have only been utilized for a production run of 4 blades whereas a typical mold is used for 400-1000 blades. Further research and experimentation is required to determine if the quality of the additively manufactured molds is as-or-more durable than the conventionally manufactured molds. Blade re-work is also an issue during production where further work needs to be done on the blade in order to meet high quality standards, further research on comparisons between re-work needed through both types of molds would be valuable for a blade manufacturer to understand before making a major investment decision.

Integration of Additional Features to Assist Blade Production

The demonstrative blade molds were able to successfully integrate heating capabilities into the blade mold, further research and exploration to add other capabilities would be valuable and would make the business case for switching to this type of manufacturing more attractive.

Direct Additive Manufacturing Finished Components

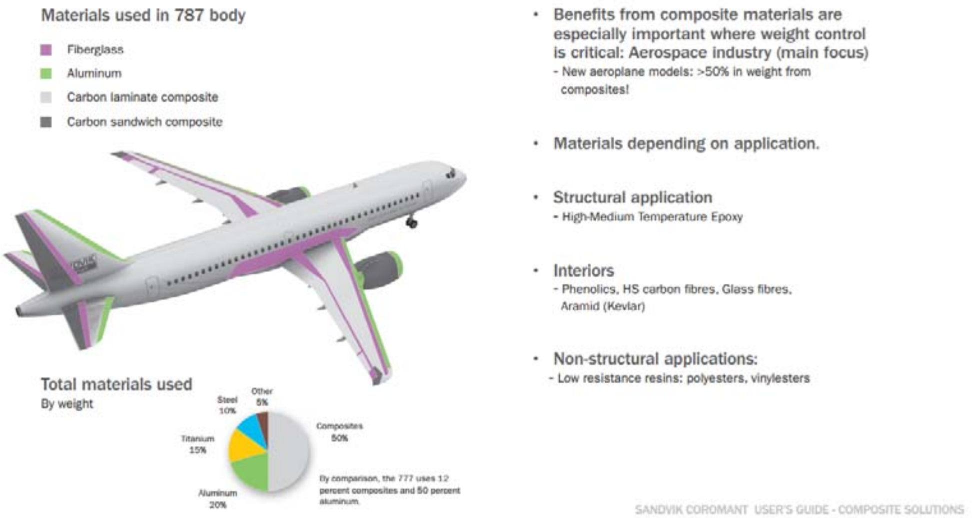
Our discussions with project leads on the demonstrative 13-meter mold revealed that they had also printed a wind turbine nacelle as a finished component. A cost comparative analysis or technical feasibility analysis has not been evaluated in this thesis however the potential utilization of this technology to produce finished parts offers a potential to further utilize additive manufacturing to reduce wind turbine manufacturing complexity, increase customizability and decrease costs. With increasing capacities and printing speeds for metal, further direct component printing will likely become more and more attractive particularly in cases where additive manufacturing is necessary to produce complex geometries resulting in more efficient components or components that have longer lifespans. Examples of such in practice are a component of a ORNL’s power inverter additively manufactured resulting in higher efficiency.

Environmental Impact

Wind energy currently boasts a very low CO2 impact relative to other energy sources. Therefore, keeping it that way or decreasing it is important as CO2 has become part of the key decision criteria for governments and business' new energy investments. Our research on additive manufacturing indicates that it is generally a less wasteful method of production however this is not a full indication of CO2 emissions. Therefore, it would be valuable to compute a CO2 emissions comparison between the two specific manufacturing methods.

9. Potential Application to Other Industries

The analysis on wind turbine blade production processes provides insight and paves the way for identifying additional applications for of use of additive manufacturing in mold creation in other applications. There are many other industries which utilize composite materials and similar mold making methodologies to that of a wind turbine. Industries such as aerospace, boat hulls, & storage tanks all utilize composite materials such as carbon fibre or fiberglass.



- Benefits from composite materials are especially important where weight control is critical: Aerospace industry (main focus)
  - New aeroplane models: >50% in weight from composites!
- Materials depending on application.
- Structural application
  - High-Medium Temperature Epoxy
- Interiors
  - Phenolics, HS carbon fibres, Glass fibres, Aramid (Kevlar)
- Non-structural applications:
  - Low resistance resins: polyesters, vinylesters

SANDVIK COROMANT USER'S GUIDE - COMPOSITE SOLUTIONS

Figure 46: Use of composite components in BOEING 787 Dreamliner, Source: Sandvik Coromant

The use of composites within aerospace has increased dramatically over the past few years, largely due to their lower cost and lower density than alternative metals resulting in lower cost, lower weights, and more fuel-efficient airplanes. Airplanes therefore could potentially realize an even larger benefit than wind turbines as production numbers are typically much lower and therefore have less units to spread the mold and plug cost over. For example, the Boeing 787 Dreamliner has a monthly production of 14 per month giving an annual production of 168 (Gates, 2017). With each composite component likely having its own plug and mold(s) and assuming a similar useful production life in units of production as wind turbines, it would take nearly 6 years before a single mold has been fully utilized. Therefore, not only would it possibly be cheaper to produce these molds through additive manufacturing but also encourage design improvements over time. For example; if new part designs were discovered that increased efficiency or decreased costs; it may be difficult to financially justify the production of a new plug and set of molds, conversely, however, if the cost was lower and multiple molds were not made of the exact same design in efforts to fully utilize the value of the plug this may be a more economically attractive strategy. It is further worth noting that plane manufacturers have already taken note of the opportunity to utilize additive manufacturing as Boeing has already begun experimenting with it in production of its 777X passenger jet (ORNL, 2016).

10. Conclusions

Through our analysis we have identified that the use of additive manufacturing applied specifically to the production of blade molds would bring 5 key opportunities to the wind energy industry:

(1) **Cost**: The cost comparison model between traditionally produced molds and additively manufactured version results in a cost savings of approximately $1 million USD per mold.

(2) **Time**: The time to produce an additively manufactured blade mold is shorter than traditionally produced molds, allowing for sooner production of the most efficient blades

(3) **Enabling Innovation**: The reduced costs and simplification of the mold production processes along with the freedom of customization allows designers to more easily experiment with different designs and make improvements based on learnings from prior designs.

(4) **Enabling Customization**: The comparative study between the two manufacturing methods highlights that with the additively manufactured method it is easier and simpler to customize blade molds and therefore tailor blades to their local environment.

(5) **Enabling of On-Or-Near-Site Production**: The new manufacturing technique allows for molds to be shipped in pieces or printed on-site, this potentially allows for installations of wind turbine farms in locations not previously accessible.

All of these opportunities are in line with our literature review of both wind energy as well as additive manufacturing. The result of a cost reduction to the mold cost and therefore blade cost and overall turbine cost resulting in a reduction to the LCOE (Levelized Cost of Energy) of wind energy is only one part of cost reduction that could be realized through additive manufacturing. While the technology to produce the mold in this method is still developing, the demonstrative blade molds produced by the ORNL exemplify that the technology has reached a suitable level to be utilized in this area. Manufactures who are early adopters will benefit in the short term with lower costs, a simpler, leaner supply chain and in the long term by obtaining a deep understanding of additive manufacturing methodology and enable them to apply the technology to other areas of manufacturing. Furthermore, it is likely that if the wind energy industry adopts this technology that the additive manufacturing industry will respond by producing machinery that is better suited for this specific application.

The impact of a simpler supply chain and lower LCOE for wind energy electricity generation would bring a significant societal benefit, as it would incentivize governments and business to make electricity generation investments in this area rather than in competing generation methods such as coal or natural gas resulting in reduced CO2 emissions.

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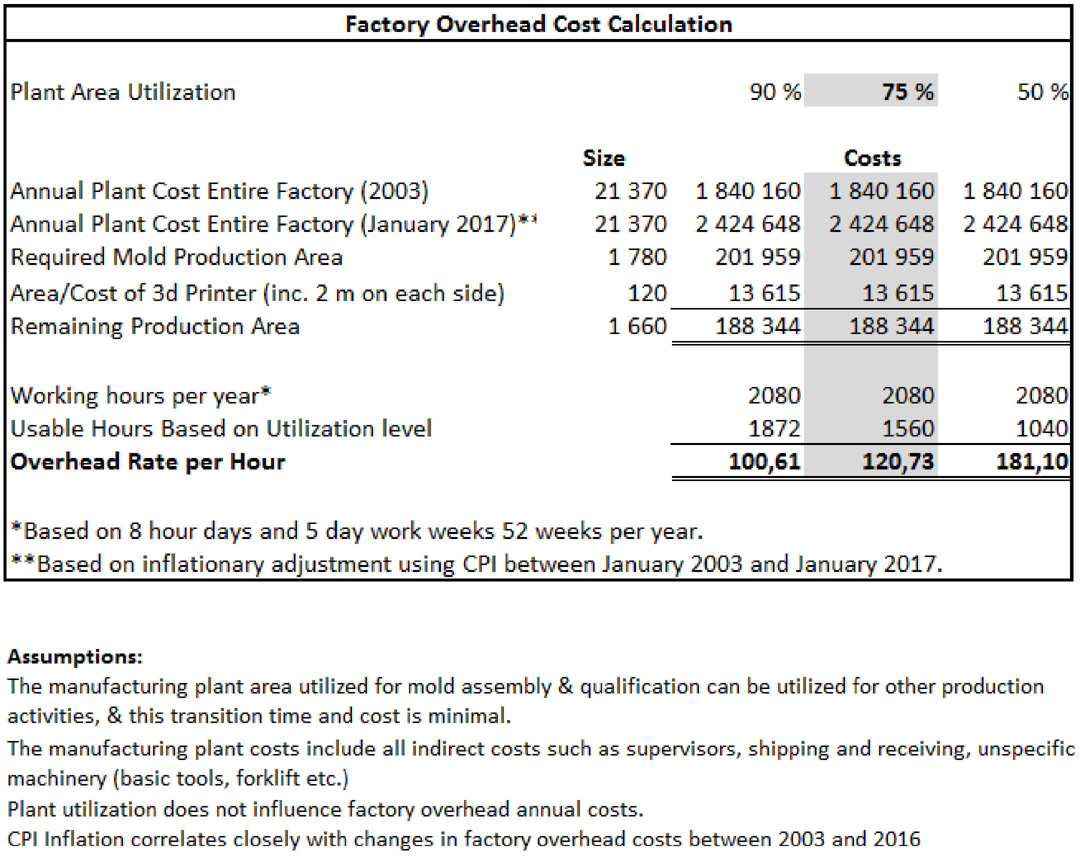
12. Appendix A



Factory Overhead Cost Calculation				
Plant Area Utilization		90 %	**75 %**	50 %
	Size		**Costs**	
Annual Plant Cost Entire Factory (2003)	21 370	1 840 160	1 840 160	1 840 160
Annual Plant Cost Entire Factory (January 2017)**	21 370	2 424 648	2 424 648	2 424 648
Required Mold Production Area	1 780	201 959	201 959	201 959
Area/Cost of 3d Printer (inc. 2 m on each side)	120	13 615	13 615	13 615
Remaining Production Area	1 660	188 344	188 344	188 344
Working hours per year*		2080	2080	2080
Usable Hours Based on Utilization level		1872	1560	1040
Overhead Rate per Hour		**100,61**	**120,73**	**181,10**

*Based on 8 hour days and 5 day work weeks 52 weeks per year.

**Based on inflationary adjustment using CPI between January 2003 and January 2017.

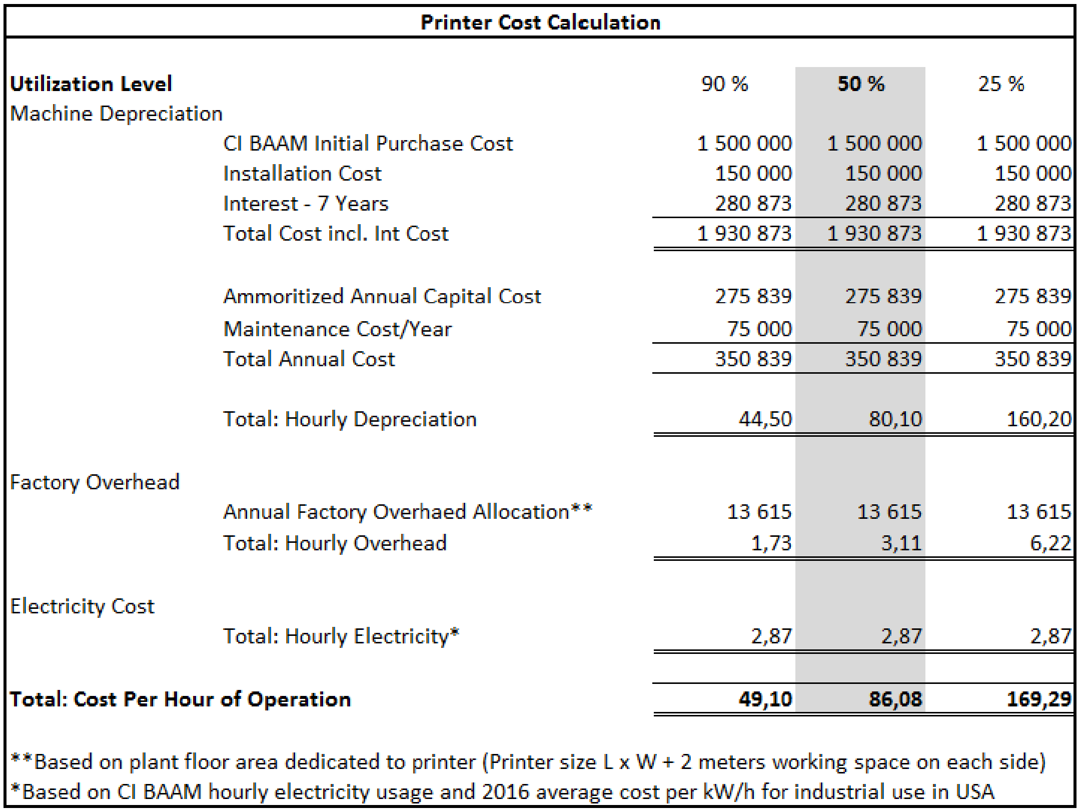
Assumptions:

The manufacturing plant area utilized for mold assembly & qualification can be utilized for other production activities, & this transition time and cost is minimal.

The manufacturing plant costs include all indirect costs such as supervisors, shipping and receiving, unspecific machinery (basic tools, forklift etc.)

Plant utilization does not influence factory overhead annual costs.

CPI Inflation correlates closely with changes in factory overhead costs between 2003 and 2016

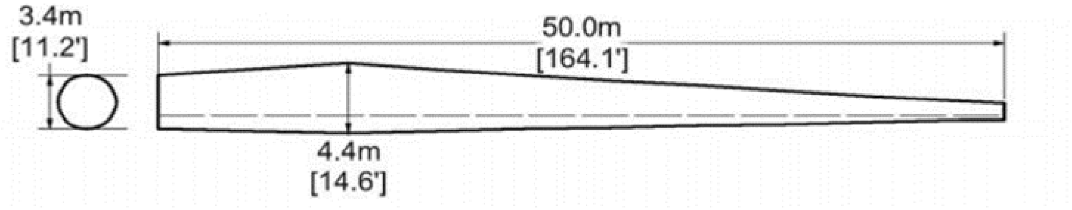


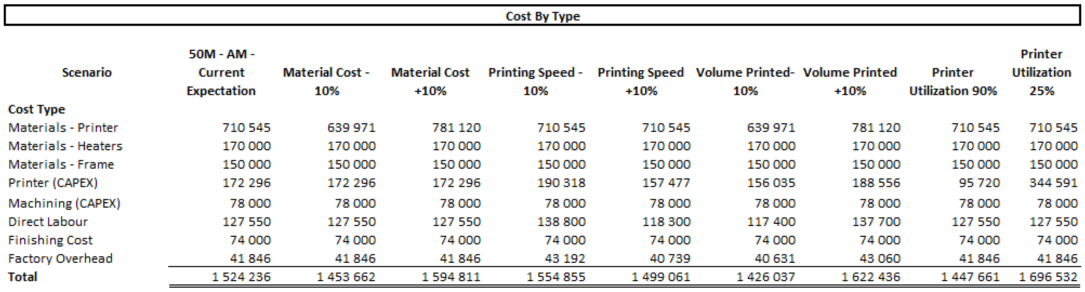
Printer Cost Calculation

Utilization Level		90 %	**50 %**	25 %
Machine Depreciation				
	CI BAAM Initial Purchase Cost	1 500 000	1 500 000	1 500 000
	Installation Cost	150 000	150 000	150 000
	Interest - 7 Years	280 873	280 873	280 873
	Total Cost incl. Int Cost	1 930 873	1 930 873	1 930 873
	Ammoritized Annual Capital Cost	275 839	275 839	275 839
	Maintenance Cost/Year	75 000	75 000	75 000
	Total Annual Cost	350 839	350 839	350 839
	Total: Hourly Depreciation	44,50	80,10	160,20
Factory Overhead				
	Annual Factory Overhaed Allocation**	13 615	13 615	13 615
	Total: Hourly Overhead	1,73	3,11	6,22
Electricity Cost				
	Total: Hourly Electricity*	2,87	2,87	2,87
Total: Cost Per Hour of Operation		**49,10**	**86,08**	**169,29**

**Based on plant floor area dedicated to printer (Printer size L x W + 2 meters working space on each side)
*Based on CI BAAM hourly electricity usage and 2016 average cost per kW/h for industrial use in USA

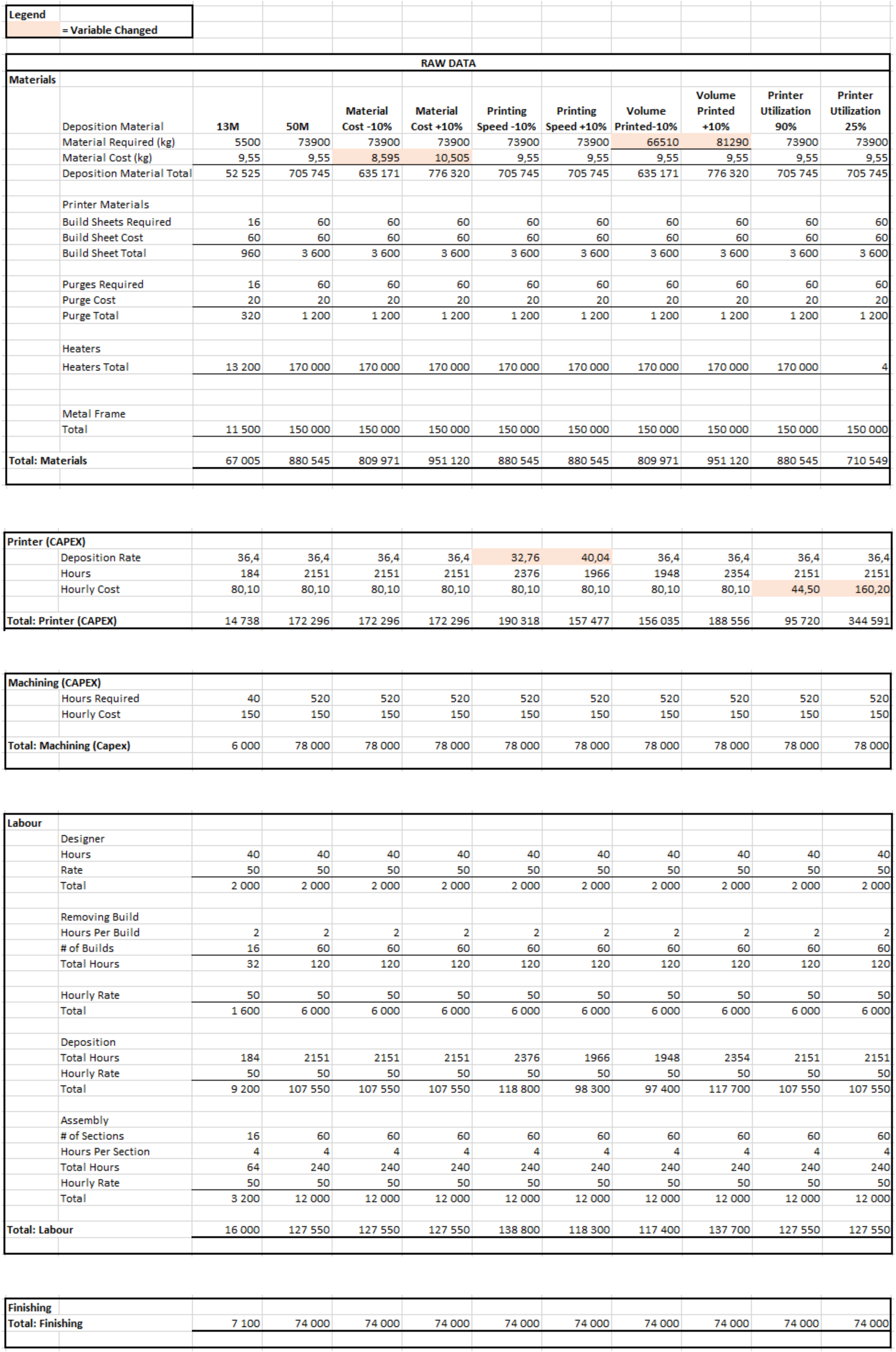
Blade Measurements Used for Mold





Cost By Type

Scenario	50M - AM - Current Expectation	Material Cost - 10%	Material Cost +10%	Printing Speed - 10%	Printing Speed +10%	Volume Printed- 10%	Volume Printed +10%	Printer Utilization 90%	Printer Utilization 25%
Cost Type									
Materials - Printer	710 545	639 971	781 120	710 545	710 545	639 971	781 120	710 545	710 545
Materials - Heaters	170 000	170 000	170 000	170 000	170 000	170 000	170 000	170 000	170 000
Materials - Frame	150 000	150 000	150 000	150 000	150 000	150 000	150 000	150 000	150 000
Printer (CAPEX)	172 296	172 296	172 296	190 318	157 477	156 035	188 556	95 720	344 591
Machining (CAPEX)	78 000	78 000	78 000	78 000	78 000	78 000	78 000	78 000	78 000
Direct Labour	127 550	127 550	127 550	138 800	118 300	117 400	137 700	127 550	127 550
Finishing Cost	74 000	74 000	74 000	74 000	74 000	74 000	74 000	74 000	74 000
Factory Overhead	41 846	41 846	41 846	43 192	40 739	40 631	43 060	41 846	41 846
Total	1 524 236	1 453 662	1 594 811	1 554 855	1 499 061	1 426 037	1 622 436	1 447 661	1 696 532



Legend	
🟧	= Variable Changed

RAW DATA

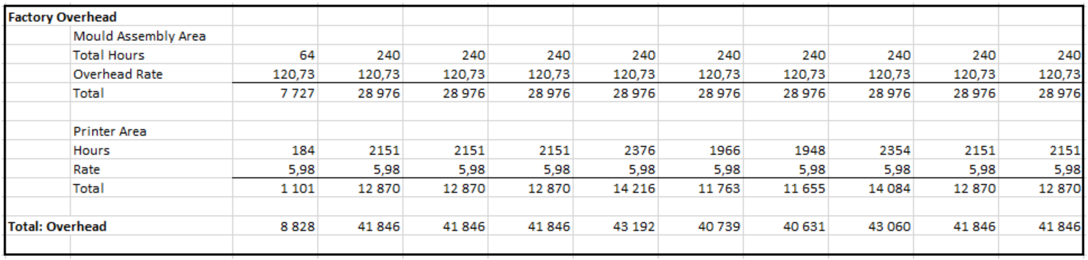
Materials											
	Deposition Material	**13M**	**50M**	**Material Cost -10%**	**Material Cost +10%**	**Printing Speed -10%**	**Printing Speed +10%**	**Volume Printed-10%**	**Volume Printed +10%**	**Printer Utilization 90%**	**Printer Utilization 25%**
	Material Required (kg)	5500	73900	73900	73900	73900	73900	66510	81290	73900	73900
	Material Cost (kg)	9,55	9,55	8,595	10,505	9,55	9,55	9,55	9,55	9,55	9,55
	Deposition Material Total	52 525	705 745	635 171	776 320	705 745	705 745	635 171	776 320	705 745	705 745
	Printer Materials										
	Build Sheets Required	16	60	60	60	60	60	60	60	60	60
	Build Sheet Cost	60	60	60	60	60	60	60	60	60	60
	Build Sheet Total	960	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600
	Purges Required	16	60	60	60	60	60	60	60	60	60
	Purge Cost	20	20	20	20	20	20	20	20	20	20
	Purge Total	320	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200
	Heaters										
	Heaters Total	13 200	170 000	170 000	170 000	170 000	170 000	170 000	170 000	170 000	4
	Metal Frame										
	Total	11 500	150 000	150 000	150 000	150 000	150 000	150 000	150 000	150 000	150 000
Total: Materials		67 005	880 545	809 971	951 120	880 545	880 545	809 971	951 120	880 545	710 549

Printer (CAPEX)											
	Deposition Rate	36,4	36,4	36,4	36,4	32,76	40,04	36,4	36,4	36,4	36,4
	Hours	184	2151	2151	2151	2376	1966	1948	2354	2151	2151
	Hourly Cost	80,10	80,10	80,10	80,10	80,10	80,10	80,10	80,10	44,50	160,20
Total: Printer (CAPEX)		14 738	172 296	172 296	172 296	190 318	157 477	156 035	188 556	95 720	344 591

Machining (CAPEX)											
	Hours Required	40	520	520	520	520	520	520	520	520	520
	Hourly Cost	150	150	150	150	150	150	150	150	150	150
Total: Machining (Capex)		6 000	78 000	78 000	78 000	78 000	78 000	78 000	78 000	78 000	78 000

Labour											
	Designer										
	Hours	40	40	40	40	40	40	40	40	40	40
	Rate	50	50	50	50	50	50	50	50	50	50
	Total	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000
	Removing Build										
	Hours Per Build	2	2	2	2	2	2	2	2	2	2
	# of Builds	16	60	60	60	60	60	60	60	60	60
	Total Hours	32	120	120	120	120	120	120	120	120	120
	Hourly Rate	50	50	50	50	50	50	50	50	50	50
	Total	1 600	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000
	Deposition										
	Total Hours	184	2151	2151	2151	2376	1966	1948	2354	2151	2151
	Hourly Rate	50	50	50	50	50	50	50	50	50	50
	Total	9 200	107 550	107 550	107 550	118 800	98 300	97 400	117 700	107 550	107 550
	Assembly										
	# of Sections	16	60	60	60	60	60	60	60	60	60
	Hours Per Section	4	4	4	4	4	4	4	4	4	4
	Total Hours	64	240	240	240	240	240	240	240	240	240
	Hourly Rate	50	50	50	50	50	50	50	50	50	50
	Total	3 200	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000
Total: Labour		16 000	127 550	127 550	127 550	138 800	118 300	117 400	137 700	127 550	127 550

Finishing											
Total: Finishing		7 100	74 000	74 000	74 000	74 000	74 000	74 000	74 000	74 000	74 000



Factory Overhead											
	Mould Assembly Area										
	Total Hours	64	240	240	240	240	240	240	240	240	240
	Overhead Rate	120,73	120,73	120,73	120,73	120,73	120,73	120,73	120,73	120,73	120,73
	Total	7 727	28 976	28 976	28 976	28 976	28 976	28 976	28 976	28 976	28 976
	Printer Area										
	Hours	184	2151	2151	2151	2376	1966	1948	2354	2151	2151
	Rate	5,98	5,98	5,98	5,98	5,98	5,98	5,98	5,98	5,98	5,98
	Total	1 101	12 870	12 870	12 870	14 216	11 763	11 655	14 084	12 870	12 870
Total: Overhead		8 828	41 846	41 846	41 846	43 192	40 739	40 631	43 060	41 846	41 846

Notes:

1. Deposition material & original deposition rate required based on discussion with ORNL staff.

2. Heater cost based on discussions with ORNL staff.

3. 3D printer capital, installation and maintenance costs based on discussions with ORNL staff.

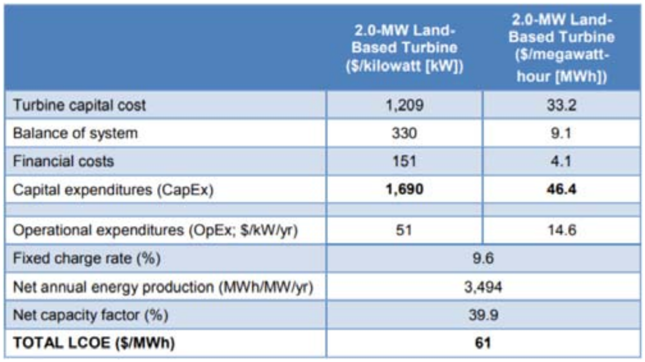
4. Machining & Finishing costs based on discussion with ORNL staff.

5. Factory Overhead 2003 cost based on Sandia National Labratories report: Cost Study for Large Wind Turbine Blades: WindPACT Blade System Design Studies, 2003

13. Appendix B

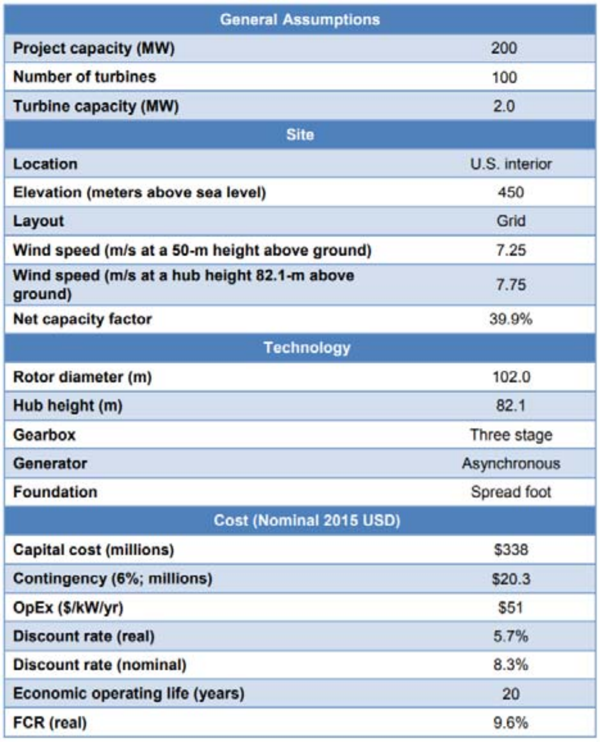
LCOE Assumptions for LCOE Model

Summary:



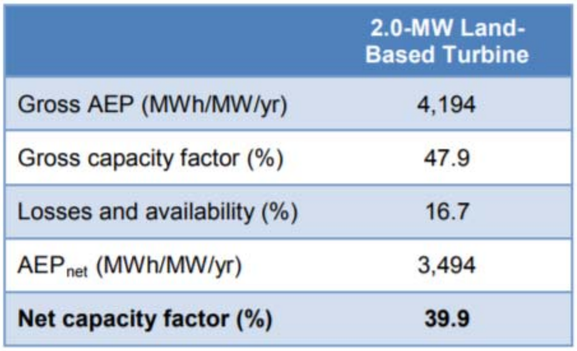
	2.0-MW Land-Based Turbine ($/kilowatt [kW])	2.0-MW Land-Based Turbine ($/megawatt-hour [MWh])
Turbine capital cost	1,209	33.2
Balance of system	330	9.1
Financial costs	151	4.1
Capital expenditures (CapEx)	**1,690**	**46.4**
Operational expenditures (OpEx; $/kW/yr)	51	14.6
Fixed charge rate (%)	9.6	
Net annual energy production (MWh/MW/yr)	3,494	
Net capacity factor (%)	39.9	
TOTAL LCOE ($/MWh)	**61**	

CapEx, Site Conditions:



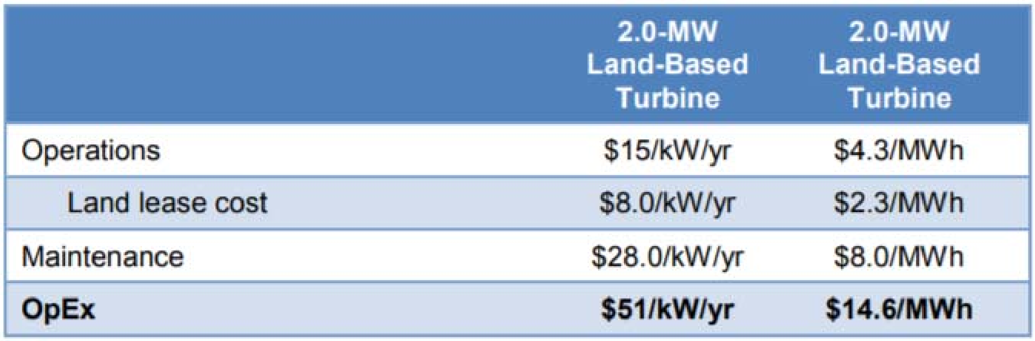
General Assumptions	
Project capacity (MW)	200
Number of turbines	100
Turbine capacity (MW)	2.0
Site	
Location	U.S. interior
Elevation (meters above sea level)	450
Layout	Grid
Wind speed (m/s at a 50-m height above ground)	7.25
Wind speed (m/s at a hub height 82.1-m above ground)	7.75
Net capacity factor	39.9%
Technology	
Rotor diameter (m)	102.0
Hub height (m)	82.1
Gearbox	Three stage
Generator	Asynchronous
Foundation	Spread foot
Cost (Nominal 2015 USD)	
Capital cost (millions)	$338
Contingency (6%; millions)	$20.3
OpEx ($/kW/yr)	$51
Discount rate (real)	5.7%
Discount rate (nominal)	8.3%
Economic operating life (years)	20
FCR (real)	9.6%

Capacity Factor:



	2.0-MW Land-Based Turbine
Gross AEP (MWh/MW/yr)	4,194
Gross capacity factor (%)	47.9
Losses and availability (%)	16.7
AEP_{net} (MWh/MW/yr)	3,494
Net capacity factor (%)	**39.9**

Maintenance & Operations:



	2.0-MW Land-Based Turbine	2.0-MW Land-Based Turbine
Operations	$15/kW/yr	$4.3/MWh
Land lease cost	$8.0/kW/yr	$2.3/MWh
Maintenance	$28.0/kW/yr	$8.0/MWh
OpEx	**$51/kW/yr**	**$14.6/MWh**

Note: Assumed cost savings are passed down directly to turbine purchaser.