# Evaluating the Green Energy Potential of the DOT type wind turbine for Mining Operations

by

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# Abstract

Applying wind turbines to create renewable energy is used by many companies around the world. However, in the mining industry, only two projects use wind energy. In the mining industry, energy consumption can be up to twenty-five megawatts per tonne of produced material. The main reason is the use of fossil fuel for generators in off-grid situations.

This paper evaluates the benefits of wind power for mining operations and the benefits of the Delft Offshore Turbine (DOT) type wind turbine compared to other turbines. Using the DOT type wind turbine, wind energy can be used for three different applications, namely: 1) generation of electricity, 2) direct hydraulic power and 3) direct dewatering.

Different areas in the world are then analysed on the aspects: 1) soil strength, 2) elevation or relief of the terrain and 3) the wind velocities. A case study is performed for the most suitable area in the world: Australia. Next the best-chosen location is divided into smaller regions, where the same evaluation is applied. A case study was conducted on a favourable area, calculating various cost and $CO_2$ reduction scenarios based on simulated wind speeds.

The DOT type turbine can provide electricity, which costs 23 to 44 US$/MWh. Compared to a 1-MW diesel generator, in the best-case scenario, a wind farm generating 25 MW per hour, can save $4200/hour. Overall, implementing the DOT at the right location, can 1) remove polluting diesel generators from mining operations, 2) save energy costs up to $4200/hour and 3) reduce $CO_2$ emissions up to 770 kilograms per MW per hour.

# Table of Contents

**ABSTRACT** .......... **III**

**1 INTRODUCTION** .......... **1**
1.1 ENERGY USE IN THE MINING INDUSTRY .......... 2
1.2 WIND ENERGY .......... 2

**2 ENERGY USE IN THE MINING INDUSTRY** .......... **4**
2.1 GENERAL INFORMATION .......... 4
2.2 DISTRIBUTION OF DIFFERENT LEVELS OF OPERATION IN MINES .......... 5
*2.2.1 Overall distribution* .......... *6*
*2.2.2 Distribution categorized by mining type* .......... *7*
*2.2.3. Distribution categorized by use of flotation* .......... *7*
*2.2.4 Distribution categorized by mined ore* .......... *8*
*2.2.5 Evaluation of costs compared to mine-life* .......... *8*
2.3 COSTS .......... 10
*2.3.1 Open pit mining* .......... *10*
*2.3.2 Underground mining* .......... *11*
*2.3.3 Off-grid mining* .......... *11*

**3 DELFT OFFSHORE TURBINE (DOT)** .......... **13**

**4 DOT TYPE WIND TURBINE FOR MINING APPLICATIONS** .......... **14**
4.1 INTRODUCTION .......... 14
4.2 DIRECT DEWATERING .......... 15
4.3 HYDRAULIC SYSTEM .......... 17
4.4 ELECTRICITY .......... 18

**5 OPPORTUNE MINING REGIONS FOR THE DOT** .......... **20**
5.1 SOUTH ALASKA .......... 22
5.2 CENTRAL AMERICA .......... 23
5.3 SOUTH ARGENTINA AND CHILE .......... 24
5.4 SOUTH ENGLAND AND NORTH-EAST FRANCE .......... 25
5.5 CENTRAL ASIA (KAZAKHSTAN AND UZBEKISTAN) .......... 26
5.6 AUSTRALIA .......... 27
5.7 SUMMARY .......... 28

**6 ECONOMIC AND ECOLOGICAL IMPACT USING SIMULATED CASE STUDIES** .......... **29**
6.1 INTRODUCTION .......... 29
6.2 METHODOLOGY .......... 30
6.3 MINING ACTIVITY .......... 32
*6.3.1 Western Australia (Northern Part)* .......... *33*
*6.3.2 Western Australia (Southern Part)* .......... *34*
*6.3.3 Tasmania* .......... *34*
*6.3.4 New South Wales and Victoria* .......... *35*
*6.3.5 Queensland* .......... *35*
*6.3.6 South Australia* .......... *36*
*6.3.7 Northern Territories* .......... *36*
6.4 DISTRIBUTION .......... 37
6.5 BEST LOCATION .......... 39
6.6 COMPARISON OF COSTS FOR ENERGY SOURCES .......... 40
6.7 REDUCTION OF COSTS .......... 42
6.8 REDUCTION OF $CO_2$ .......... 43
6.9 DIRECT INTERNAL HYDRAULIC NETWORK .......... 44

**7 CONCLUSION** .......................................................................................................... **46**

**8 BIBLIOGRAPHY** .......................................................................................................... **47**

**9 APPENDICES** .......................................................................................................... **49**

9.1 APPENDIX A – SCREENSHOT SF PRESSURE DROP SOFTWARE ........................................................ 49

# 1 Introduction

For decades, industries have developed methods to make their production amounts greater and their efficiencies higher. Valuable resources are needed for production of almost all products in those industries. To maintain a constant supply of those materials, mining projects are needed to obtain the necessary raw materials. These operations cost much and pollute the environment by using non-renewable energy sources. Although there has been much attention to creating a greener industry that is less dependent on raw materials from mines, there has been hardly any attention to making the mining processes greener.

This paper investigates wind as a source of green energy to evaluate the potential for mining operations, with particular attention to the DOT type wind turbine. It answers the research question: What is the economic and environmental impact of using the DOT type wind turbine for the mining industry?

The aim of the research is to obtain more information for the use of wind energy for the use in mining operations. The research will provide a best location and the feasibility of such a project. The above aim will be accomplished by fulfilling the following research objectives:

1. Review literature concerning the energy use for different mining operation to know which process consumes the most energy.
2. Investigate different applications for the DOT type wind turbine.
3. Applying case studies to select the most suitable country/region.
4. Compare wind speeds of the chosen region to evaluate the potential.
5. Investigate the decrease in costs, emissions and fossil fuel usage.

This study us supposed to make clear that wind energy can be used in mining operations. Therefore, the overall energy use, different systems and case studies are evaluated. Worth mentioning is that it is hard to find scientific information about the energy use in mining projects. Also, all mining project around the world have lots of parameters for calculating their total costs. Wherefore. this study is mostly based on American studies, which are most available. Other countries are thereby left out of scope.

The research question will be answered in five chapters, starting with a brief review of energy use in the mining industry, followed by an introduction of the DOT type wind turbine and its evaluation for mining applications. Then, opportune mining regions for the DOT will be identified, followed by an evaluation of the economic and ecological impact using simulated case studies on selected areas.

## 1.1 Energy use in the mining industry

To give an idea of the total energy consumption of mining industries, the following comparison can be made; in the United States of America the mining industry used 365 billion kWh in the year 2007, according to the National Energy Bandwidth Study. For comparison, 120 billion kWh was used by the whole of the Netherlands in 2013, which is almost one-third of the consumption in the USA mining sector alone. It should be mentioned that, of course, the United States is approximately 235 times bigger than the Netherlands.

In Chile, the mining industry has big impacts, too. The paper “The Energy Use in Premanufactured Mining” (Jeswiet, Archibald, Thorley, & De Souza, 2015) states that around 32 percent of their total energy consumption is used for the mining industry, which is circa 22 billion kWh per year. In 2014 in the northern part of Chile, 90 percent of the generated electricity was used by the mining industry. Cheaper energy sources are needed; it is expected that by 2025 the copper industry will be using 41 terawatt-hours, which is an increase of 95.5% compared to the usage in 2013 (Jeswiet & Szekeres, 2016).

## 1.2 Wind energy

A cheaper, greener energy source is wind energy. Wind energy has been used as early as the tenth century (Lynn, 2012). Over the past century, there have been many developments in wind engineering leading to increasingly more efficient wind turbines. According to the World Wind Energy Association, at the end of 2016, five percent of the world’s electricity demand was generated by wind turbines. That is an 11.8 percent growth rate compared to the year before. This shows that wind energy is becoming a more important green energy source.

According to the Lazard Levelized Cost of Energy Analysis (2016), wind energy is one of the cheapest energy sources compared to all other sources considered, as seen in figure 1. The estimated range of costs is 32 to 62 US$/MWh.

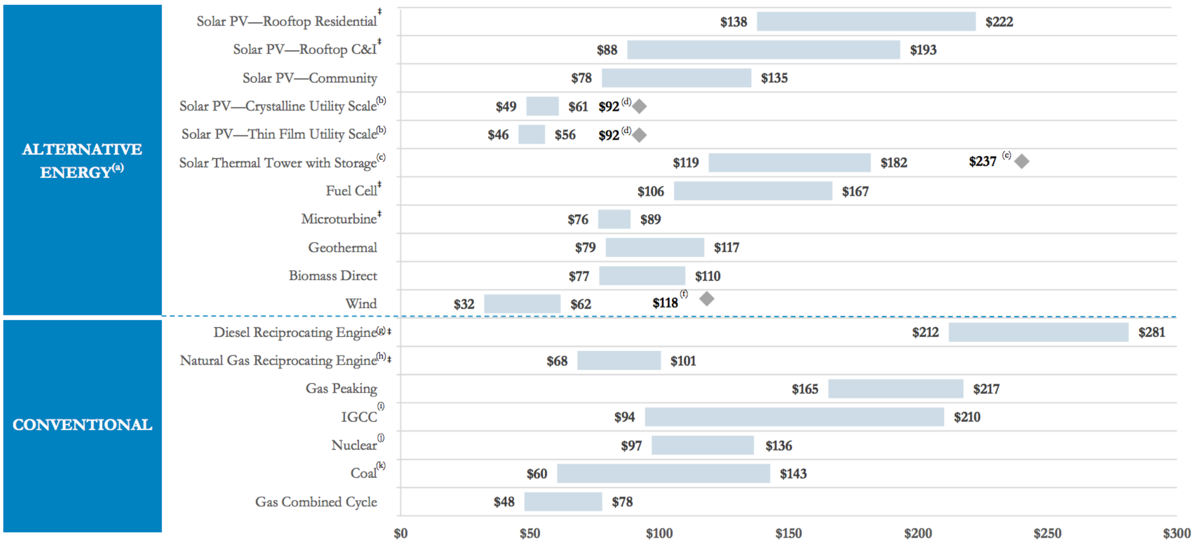


*Figure 1. Levelized Costs of Electricity (US$/MWh) (Lazard, 2016)*

For mining, implementing wind energy in existing mines is a practical choice, as a wind turbine can be erected almost anywhere, as long as the conditions are right. This cannot be said for some other alternative energy sources, such as hydroelectricity, which would depend on water near the mine. Another advantage of the DOT wind turbine is that with its innovative system, using only a pump in the nacelle, it can be used for other techniques than the generation of electricity alone. This will be discussed further in chapter

It is likely that in the future it will be mandatory to use renewable energy sources. The main goal of the current climate agreement of Paris is the reduction of $CO_2$ emissions to net-zero in the second half of this century (Streck, 2015). Most off-grid mining sites are now powered by polluting generators, using fossil fuels like diesel, petrol and natural gasses, and on-grid facilities use electricity which is generated with polluting sources. The usage of wind energy in different mining operations can be a necessary addition to the polluting sector.

# 2 Energy use in the mining industry

This chapter will give a review of energy use in the mining industry. This will make clear that the mining industry uses mainly non-renewable fuels. It will also provide an indication of costs now made. Further, different subsections of the mining processing are evaluated for their energy consummation.

## 2.1 General information

Though sources that give an overview of the fuel usage in mines are hard to come by, BCS Incorporated did a study in 2007 in the USA that gives an indication. Though it is only one country, it is still interesting to consider this data. The study shows that the major energy sources for the mining industries in the USA are petroleum products, electricity (purchased and produced onsite), coal and natural gas (BCS, Incorparated, 2007). The type of fuel is dependent on the type of mine and on the process which is applied. Looking at figure 2 (BCS, Incorparated, 2007), the fuel consummation in the mining industry can be seen.

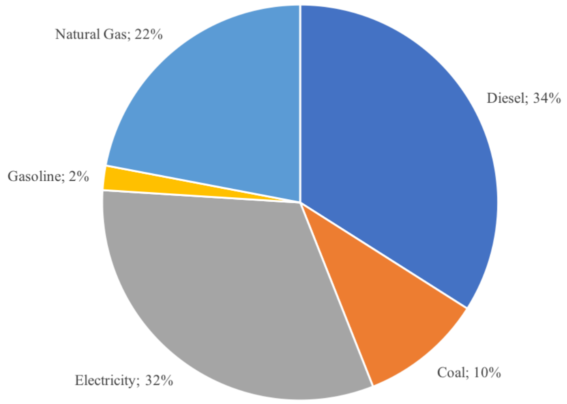


*Figure 2. Fuels Consumed in the Mining Industry of the United States of America. (BCS, Incorparated, 2007)*

Keeping in mind that most mines cannot be connected to the grid because they are located in remote areas, electricity is not the largest energy source. Diesel consumes the largest part of overall costs. In remote areas, it can be harder to get electrical power to the mine. This is then done with the help of generators using diesel or natural gas.

Looking at the total usage of the energy in the USA, which is 330 milliard kWh (BCS, Incorporated, 2002), which is 3.3 percent of the total energy market, the conclusion is that energy is the backbone of mining operations. Though gasoline is a small contributor in comparison to the other energy sources, there is always equipment that can only run on gasoline, which are mostly light vehicles. Natural gas and diesel are the main energy sources for the generators which convert them into electricity.

## 2.2 Distribution of different levels of operation in mines

To identify the mining process that consumes the most energy, an overview of the different stages and their consumption are given below. This is done so an oriented approach for making those processes less dependent on fossil fuels can be made. Figure 3 displays the main components that can be identified;

- *Beneficiation & Processing*, which is any process that improves impurities from the ore, so that in the end the grade and value will be higher.
- *Extraction*; which is any process that is involved in the extraction and transportation from the raw material to the processing site.
- *Materials Handling*; which is any process that is related to handling of the raw materials, which comes mostly down to making enough material in the required quality available within the given timespan.

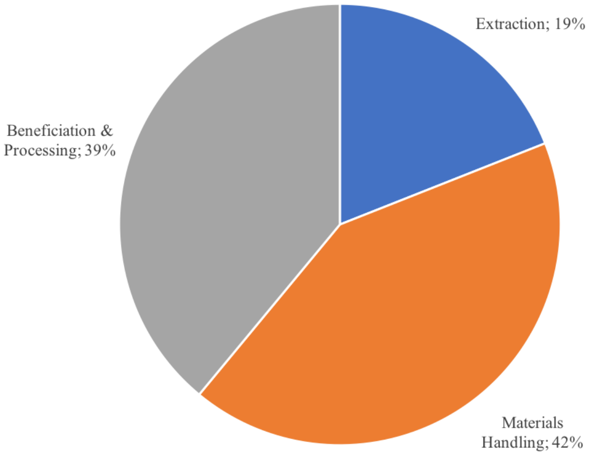


*Figure 3.Estimated Energy Consumption by Stage (Percent of Total Energy Requirements) (Jeswiet, Archibald, Thorley, & De Souza, 2015)*

Of these three categories, some are more suitable to adapt to wind energy than others. For the extraction process, it is challenging to use wind energy; in most mines dynamite or other explosives are used to break the rocks loose from their formation, which is hard to do with other methods. Transportation is also not eligible, as hauling vehicles run on fossil fuels, which are expensive to replace or to modify. There are currently projects with hauling trucks that run on fuel cells powered by electricity, but it is difficult and expensive to implement in the current fleet.

Material handling and the beneficiation and processing stages are more interesting to evaluate. These do not involve moving vehicles, but include mostly stationary equipment which can more easily be connected to wind turbines. Therefore, a closer look is necessary to identify the different components of these categories.

As seen in figure 3, the materials handling and beneficiation and processing are the most energy consuming. The article "Mine operating costs and the potential impacts of energy and grinding" (Curry, Ismay, & Jameson, 2013) also evaluates different categories in various countries around the world. The paper takes into consideration the overall distribution, mine type, processing type, and the effect of time, using three main components;

- *Mining*; Drilling, blasting, loading, hauling, equipment maintenance and repair, mine overheads, mine specific labour requirements.
- *Milling*; Power, grinding media and mill linings, consumables, reagents, equipment maintenance and repair, maintenance materials, milling specific labour, milling overheads.
- *General and Administration (G&A)*; Management costs, staffing for human resources, environment, health and safety, training, communications, community relations, camp and catering, mobile equipment, insurance.

### 2.2.1 Overall distribution

For the mining costs in these 63 cases, table 1 gives the sole distributions of the components, including the mean, median, range and 95% confidence level. The values of table 1 are also presented graphically in figure 4, where the maximum and minimum values can be seen, with the median as the solid line in the middle of the box, and the mean as the dotted line.

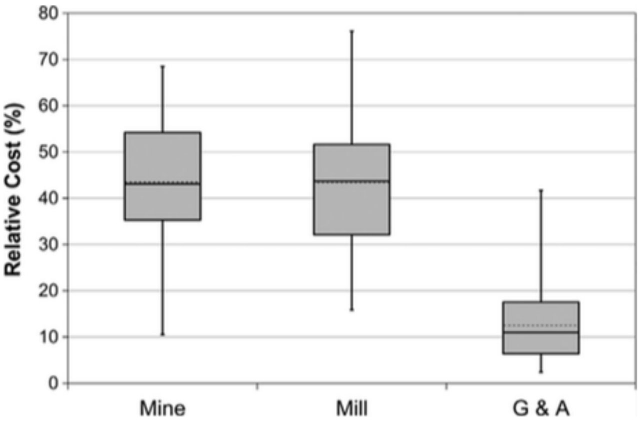


*Figure 4. Distributions of the different levels of operation for 63 mines. (Curry, Ismay, & Jameson, 2013)*

| | Mean (%) | Median (%) | Range (%) | 95% Confidence interval |
|---|---|---|---|---|
| Mine | 43.2 | 43.1 | 57.9 | ± 3.4 |
| Mill | 43.5 | 43.7 | 60.3 | ± 3.8 |
| G & A | 13.3 | 11.0 | 39.3 | ± 2.2 |

*Table 1. Distributions of the costs of different levels of operation for 63 mines. (Curry, Ismay, & Jameson, 2013)*

As is shown in figure 4, the mining and milling costs are significantly higher than the general and administration costs. Other differences within the milling costs can be evaluated by looking at the mining type.

### 2.2.2 Distribution categorized by mining type

Table 2 evaluates the same information as in table 1, but categorized by mining type.

| | n | Mean (%) | Median (%) | 95% Confidence Interval |
|---|---|---|---|---|
| **Mine** | | | | |
| Open pit | 41 | 40.3 | 42.3 | ±4.6 |
| Underground | 9 | 51.5 | 55.6 | ±11.4 |
| Both | 11 | 47.9 | 47.7 | ±5.9 |
| **Mill** | | | | |
| Open pit | 41 | 48.9 | 49.5 | ±4.6 |
| Underground | 9 | 34.1 | 35.1 | ±8.3 |
| Both | 11 | 39.3 | 39.0 | ±6.6 |
| **General and Administration** | | | | |
| Open pit | 41 | 10.8 | 9.5 | ±1.6 |
| Underground | 9 | 14.4 | 14.6 | ±5.5 |
| Both | 11 | 12.8 | 11.7 | ±4.9 |

*Table 2. Distributions of the costs for different levels of operation for 63 mines categorized by mine type. (Curry, Ismay, & Jameson, 2013)*

The milling costs in an open pit environment are higher than those of the other mines. The costs of G&A are similar per mine type, which is also found for the mining costs.

### 2.2.3. Distribution categorized by use of flotation

To determine possible differences in the processing types, the costs are discussed for mines using flotation and mines using no flotation, which is equipment that uses a lot of electrical energy to keep the pump running. Table 3 gives a summary of the obtained results;

| | n | Mean (%) | Median (%) | 95% Confidence interval |
|---|---|---|---|---|
| **Mine** | | | | |
| Flotation | 37 | 41.6 | 42.3 | ±4.3 |
| No flotation | 24 | 46.0 | 51.5 | ±6.8 |
| **Mill** | | | | |
| Flotation | 37 | 46.3 | 47.5 | ±4.5 |
| No flotation | 24 | 43.0 | 40.0 | ±6.8 |
| **General and Administration** | | | | |
| Flotation | 37 | 12.1 | 10.6 | ±2.4 |
| No flotation | 24 | 11.0 | 11.3 | ±2.3 |

*Table 3. Distributions of the costs for different levels of operation for 63 mines categorized by the use of flotation. (Curry, Ismay, & Jameson, 2013)*

It can be concluded that mines using flotation have lower mining costs, but have higher milling costs, as are the costs for G&A.

### 2.2.4 Distribution categorized by mined ore

The type of ore is a crucial factor in the energy use of a mine. Rare elements like gold and platinum have higher costs because their cut-off grade is low, which means a lot of dump material is generated for one unit of the required mineral. In Curry, Ismay, & Jameson (2013) the distinction between gold and copper ore is made. Copper has a higher grade than gold, with an average ore grade of 0.62 percent compared to 0.0004 percent for gold (Calco, Mudd, Valero, & Valero, 2016). Table 4 gives a summary of Curry, Ismay, & Jameson's results.

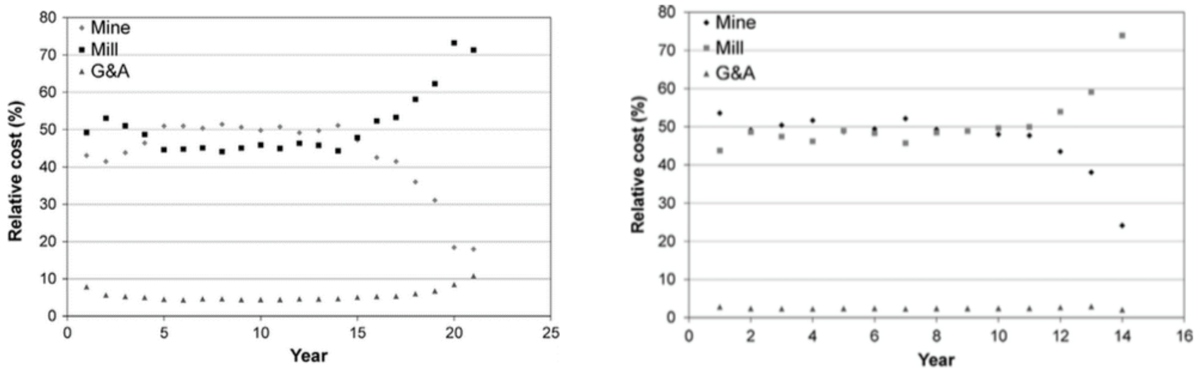
| | n | Mean (%) | Median (%) | 95% Confidence interval |
|---|---|---|---|---|
| **Mine** | | | | |
| Gold | 30 | 48.1 | 49.5 | ±4.4 |
| Copper | 24 | 37.8 | 38.5 | ±5.8 |
| **Mill** | | | | |
| Gold | 30 | 41.0 | 40.0 | ±5.0 |
| Copper | 24 | 46.4 | 47.5 | ±7.1 |
| **General and Administration** | | | | |
| Gold | 30 | 10.9 | 9.5 | ±2.6 |
| Copper | 24 | 15.8 | 13.0 | ±4.3 |

*Table 4. Distributions of the costs for different levels of operation for 63 mines categorized by mined ore. (Curry, Ismay, & Jameson, 2013)*

Table 4 confirms that the mining of gold is more expensive than copper, but the milling costs are higher for copper than gold, as are the G&A costs.

### 2.2.5 Evaluation of costs compared to mine-life

Finally, the influence of time is evaluated. Mining projects are expected to run for several years, with the consequence that toward the end costs will rise due to a higher overburden. The annual data was not available for all the mines, so two individual cases have been looked into. Figure 5 give a summary of the costs for the lifespan of a mine.



*`Figure 5. Evaluation of costs for Don Creek Mine, USA and Hosco Mine, Canada. (Curry, Ismay, & Jameson, 2013)*

A pattern can be distinguished for these two mines, in which the milling cost will rise in the end. Initially, the mining and milling costs are similar, but nearing the end, they diverge. The general and administration costs do not change along the timespan.

This study was based upon the information of 63 mines, but further examination is needed to get a clearer overview of the total costs of the mining, milling, and general and administration costs. Other case studies have revealed that the energy use is distributed very differently. Chapter 7 of the Energy Use in Copper Mines (Congress of the United States) states another model of that distribution, which is depicted in figure 6.

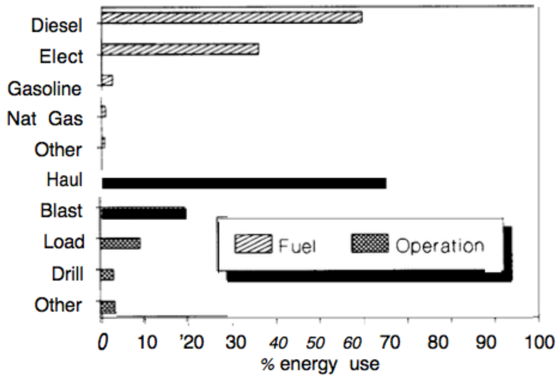
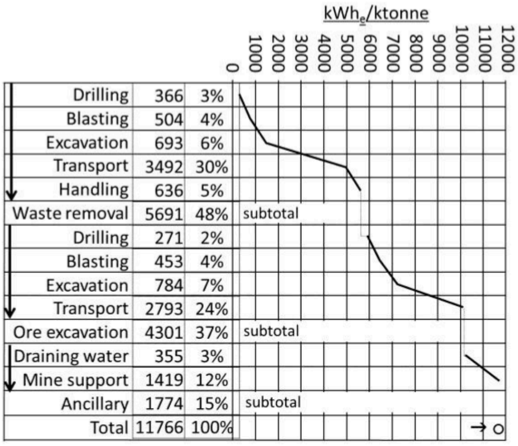


*Figure 7. Average energy use for a single open pit mining operation in the United States. (Energy Use in Copper Mining, Article)*



| | | | |
|---|---|---|---|
| Drilling | 366 | 3% | |
| Blasting | 504 | 4% | |
| Excavation | 693 | 6% | |
| Transport | 3492 | 30% | |
| Handling | 636 | 5% | |
| Waste removal | 5691 | 48% | subtotal |
| Drilling | 271 | 2% | |
| Blasting | 453 | 4% | |
| Excavation | 784 | 7% | |
| Transport | 2793 | 24% | |
| Ore excavation | 4301 | 37% | subtotal |
| Draining water | 355 | 3% | |
| Mine support | 1419 | 12% | |
| Ancillary | 1774 | 15% | subtotal |
| Total | 11766 | 100% | |

*Figure 6. Average energy use for eight open pit mining operations in the United States. (Energy Use in Premanufactured (Mining), Article)*

According to the Energy Use in Copper Mining: "Underground mines use electricity for generating compressed air, pumping, lighting, ventilation and hauling miners and materials. They also use diesel fuel for surface hauling of ore to the mill". Therefore, other assumptions have to be made for different mines. Another cost model is evaluated in the paper "Energy Use in Premanufactured Mining" (2015). This study is based on eight open pit mines in Canada. As in the previous cases, hauling is accountable for a large part of the total consumption of energy. To clarify the numbers in figure 7, the article states: "Trucks are the biggest energy consumer, hauling waste rock and ore to the surface where it is processed in a crusher. In a typical pit 70-80% of a truck's diesel use is during the uphill portion of the haul cycle". Beneficiation is done by crushing and grinding, causing separation by density, magnetic, electric or chemical methods. Crushers use circa 746 kW (1000 HP).

## 2.3 Costs

There are significant differences in cost between open pit and underground mines, mostly because underground mines need much more energy for heating, ventilation and air conditioning. However, both types of mines need pump installations ensure the water table is low enough to avoid watering of the mine. It is assumed that 25 to 32 percent of the total motor capacity of a mine is needed for pumping (Jeswiet & Szekeres, 2016)**.** For heating, ventilation and air conditioning in underground situations the energy need is almost 25 percent of the total costs. It can be concluded that the overall distribution of energy costs in mining activities is 3 to 5% for blasting, 5 to 7% for crushing and 80 to 90% for grinding, according to Jeswiet and Szekeres.

Conventional energy sources used in mining areas also have their own costs. For companies, it is necessary to find cheaper sources. Contemporary techniques make green alternatives an interesting field to find these. In order to make a convincing case, an assessment for the costs of each fuel type is needed. Below, six different fuels are discussed: bunker C oil, gasoline, diesel, blasting fuels, propane and electricity. There are different prices for open pit and underground mining. Therefore, two researches are used to show that difference. The aim of this section was a reliable and complete overview; therefore, it has to be taken into account that the data are valid for Canadian Mine Operations (Natural Resources Canada, 2005).

### 2.3.1 Open pit mining

By looking at the total costs of the different fuel types and comparing them to each other, table 5 is obtained. There are significant differences between the lowest and highest unit costs reported for the sources of energy used at the mining operations.

It can be seen that in open pit mining, electricity is by far the most used energy source, much higher than the other evaluated energy sources. This is caused by the milling process, which needs large amounts of electricity. Table 5 indicates the costs per energy source in Canadian dollar per kWh. To get a good overview of the costs within the different sections, table 6 displays the average prices of the energy sources.

| Energy Source | Price | Unit |
|---|---|---|
| Electricity | 0.044 | $/kWh |
| Diesel | 0.38 | $/litre |
| Gasoline | 0.56 | $/litre |
| Propane | 0.47 | $/litre |
| Blasting Fuels | 0.50 | $/kg of explosive |
| Bunker C Oil | 0.21 | $/litre |

*Table 5. Average values of data given in figure 4.*

The average costs for the different mining operations can be seen in table 6. This shows once again that the price per kiloton or kWh varies greatly.

| Parameter | Value | Unit |
|---|---|---|
| Energy Cost | 2343 | $ per kiloton of ore processed |
| Energy Consumption | 46352 | $kWh_e$ per kiloton of ore processed |
| Unit Energy Cost | 0.048 | $ per kWh |

*Table 6. Average values of energy consumption.*

### 2.3.2 Underground mining

For underground mining, a lot more explosives are used than in open pit mining. Therefore, more blasting fuels will be needed. Blasting fuels cannot be replaced by alternative energy sources. Eleven different mines are evaluated. Table 7 shows the average costs for the energy cost and consumption and unit costs.

| Parameter | Value | Unit |
|---|---|---|
| Energy Cost | 5.10 | $ per ton of ore hoisted |
| Energy Consumption | 95.3 | kWh per ton of ore hoisted |
| Unit Energy Cost | 0.054 | $ per kWh |

Table 7. Average values of energy consumption.

The prices of oil and electricity will decrease further in the coming years. However, this energy source is used for almost all equipment. As the grade of the ore decreases, more raw materials have to be processed, and therefore also transported, to produce the same amount of the required material. This leads to increased fuel usage, and consequentially higher costs.

### 2.3.3 Off-grid mining

Off-grid electricity generation uses large diesel generators, which are expensive and have a very low efficiency of 40 percent (Lentz, 2016). Based on 24 case studies with diesel generators, it can be said that three main components apply for the total costs of a diesel generator (Thimsen, 2003);

- An overall expected investment cost of $371/kW for diesel powered generator capacity
- Total annual diesel fuel cost is estimated at $15.34 per kW for 200 hours of operation per year with fuel costing US$1.00/gallon
- Annual maintenance costs average $5,000/year for a typical diesel engine driven 1,800 kW unit operating 200 hrs/year or less

These factors make it very expensive to mine in remote areas, such as Western Australia or Northern Canada. Data from the Arctic Energy Alliance (2015) suggests that on average, off-grid mines in Northern Canada have been 30 to 60 percent higher in costs than on-grid mines. Table 8 gives an overview of the average prices for the major cities and the remote northern part of Canada;

|  | Diesel, $/L | Electricity, %/kWh | Fuel Oil, $/L |
|---|---|---|---|
| Major City | 0.984 | 0.0951 | 0.937 |
| Remote North | 1.7 | 0.37 | 1.6 |
| Difference | 173% | 389% | 171% |

*Table 8. Percentage of overall annual operating costs for base and precious metal mines operating in remote Northern Canada. (Arctic Energy Alliance, 2015)*

With differences above an increase of 150 percent, it is important to consider the use of alternative forms of energy. Diesel generators are polluting, inefficient and cost on average almost 400 percent more than electricity from the grid. A cheaper alternative would be for example wind energy.

# 3 Delft Offshore Turbine (DOT)

This paper investigates the use of the Delft Offshore Turbine (DOT), which is a concept model and an alternative for the conventional wind turbines. In the future, this could not only be used for offshore locations, but also locations onshore where electricity or other applications are needed. The DOT is a project of which the main goal is to reduce the price of the turbine by using a technical solution. This is done by redesigning the nacelle, which is the part on top connected to the rotor blades. The costs are lowered the most by using fluid power transmission, instead of a conventional motor with an expensive gearbox. Figure 8 gives an overview of the DOT-concept.

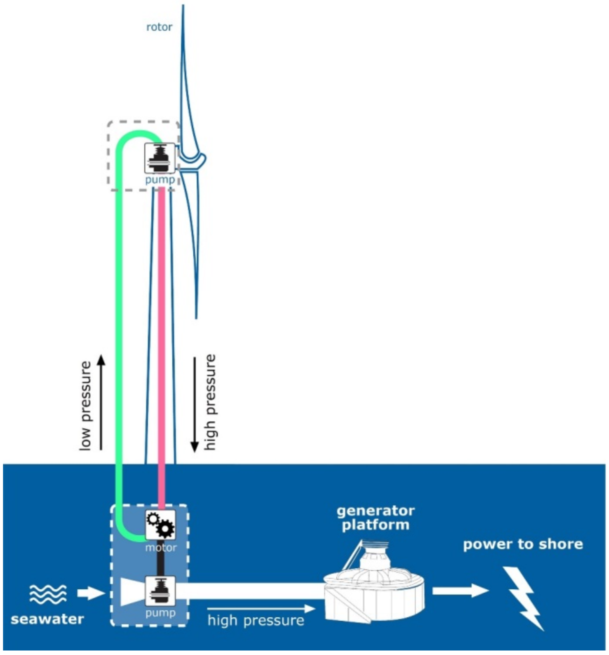


*Figure 8. Schematic overview of the DOT. (Diepeveen, Jarquin Laguna, & Kempenaar, 2012)*

The concept of the DOT consists of four main components (Kempenaar, Diepeveen, & Jarquin Laguna, 2011):

1. Rotor; this subsystem extracts the energy from the wind. In the concept, it is a 2-bladed horizontal axis rotor. The main advantage of this rotor is the reduced installation time and costs compared to the currently used 3 bladed rotors.
2. Closed-loop oil circuit; this subsystem transfers the energy from the shaft of the rotor to the base of the turbine tower.
3. Open-loop sea water circuit; this subsystem transfers the energy from the base of the turbine tower to the generator platform.
4. Generator platform; the hydraulic energy of multiple turbines come together on this generator platform. On the generator platform, the hydraulic energy is converted into electrical energy with a hydraulic turbine and generator.

# 4 DOT type wind turbine for mining applications

## 4.1 Introduction

The DOT concept could be used for several applications in the mining industry, the most important being electricity generation. As seen in chapter two, mining operations demand huge amounts of electricity in order to keep them running; both in on- and off-grid situations, electricity is used at an almost constant rate, every day of the year. The largest energy consumers are off-grid mines, where electricity is dependent on generators using fossil fuels. With the technique of the DOT, it is possible to use the energy it generates directly for electricity, direct dewatering, or the use of a direct internal hydraulic network to which equipment can be connected.

The biggest difference between conventional wind turbines and the DOT is that in the regular models, most parts are located in the nacelle. This is where, for example, the gearbox, transformer and generator are located. The main objective is that electrical energy can be provided directly from the wind turbine. The DOT only uses a pump in the nacelle, which pumps hydraulic fluid downwards under high pressure, where another pump is incited to pump sea water at high speed through a tube network. At ground level, there may be a generator that can generate the electricity. However, that might not be needed, as the hydraulic pressure from the pump in the nacelle could be directly used. This would lead to a lowering of the costs, as the movement would not have to be converted into energy that is compatible with mining equipment.

As discussed in the previous chapter, energy is essential in all areas of mining. In both surface and underground mining, almost all the equipment runs on electricity or fossil fuels. With the current energy transition, it will be necessary to develop, experiment, and continue with different energy sources, where the main objective is to make it as green as possible. With the current Paris agreement, it is clear that the production of fossil fuels will stop eventually. The plan is to phase out fossil fuels by 2050, but in the future the world will go to a non-fuel economy. For companies working in the mining sector, it is necessary to make sure they develop options which are greener than methods used today. The DOT wind turbine could play a big role in the development of these transitions, as mining areas are usually in remote places where enough wind is available.

The investment in wind turbines does not mean that the energy must be cheaper in order to continue using and investing in them. Because regulations have been set in the form of the Paris agreement, investment is needed to develop projects like the DOT. On the long term, green energy has to be profitable, but first a steady environment is needed where testing can be done before the DOT is applied on a big scale. Investment to pioneer in the field of green energy costs money, but the yield is considerable.

For conventional energy sources, efficiency is an important factor in looking at the conversion from fossil fuels to electricity. For the generation of electricity, coal, diesel oil, heavy fuel oil and natural gas is used. These variants all have their efficiencies, advantages and disadvantages. Table 9 shows the estimated efficiencies of different fuels that have been measured. This means the conversion between the fuel that is entered and the kWh that results.

| Fuel type | Estimates of contained kWh/unit of fuel | Unit | Range of efficiency estimates of fossil fuel conversion to electricity (%) | Estimated kWh/unit of fuel |
|---|---|---|---|---|
| Coal | 4,100-10,000 | t | 35-40 | 1,500-3,800 |
| Diesel oil | 9.7 | l | 35-44 | 3.8 |
| Heavy fuel oil | 12 | l | 35-44 | 4.5 |
| Natural gas | 11 | $m^3$ | 33-49 | 4.5 |

*Table 9. Estimated efficiencies for the conversion of selected fossil fuels to electricity. (EPRI, 2003)*

It can be concluded that all the above fuel types have efficiencies around 40 percent. According to the Betz limit, wind turbines are likely to have efficiencies between 75 and 80 percent. Therefore, wind energy is a more efficient alternative.

The DOT has more efficient applications. The current concept is focused on the generation of electricity, whereas other applications can be found. The following pages evaluate three different approaches for the use of the DOT turbine; direct dewatering, the use of a hydraulic motor and the generation of electricity.

## 4.2 Direct dewatering

When opening an open pit or surface mine, groundwater control is important. Since the mine is likely to fall below the water table, dewatering is needed to avoid water flowing into the mine. In some cases, control is easy and can be solved at ground location. In other cases, dewatering is one of the most important factors in making the mine feasible and safe. This is all needed to make sure a good slope stability is guaranteed. Bad dewatering policies could lead to setbacks or even closure of the mine.

Conventionally, pumping occurs with pumps that run on electricity or a fossil fuel. As mentioned earlier, the DOT concept provides a technique which uses only a pump to create a flow of high pressure through a small tube. The flow through this tube could be converted to electricity using a pelton turbine. But for dewatering options, the wind turbine could be useful to incite a hydraulic pump which can pump out the water, or to reduce the pore water pressure around the mining area.

However, pumping has to be maintained 24/7 in order to keep the mine dry. Using a direct coupling between the pump and the wind turbine would therefore carry a risk; when there is no wind, the dewatering will come to a halt. In a mining environment, this is not an option. If pumping were to stop, the groundwater level could rise to its original height, drowning the mine due to water seepage. Furthermore, a steady pumping rate is needed to make sure that enough water can be pumped out. Therefore, a good backup is needed in order to maintain pumping, even when, in the worst case, there is no wind. This could be done using an electrical backup solution through connection to the grid or using an accumulator.

Evaluating different options for dewatering, there are many hydraulic solutions that can be applied. In order to make the pumping functional, a hydraulic pump could work. This pump would then use the hydraulic pressure generated by the pump in the nacelle of the DOT. For the concept of the DOT, seawater is used to create the pressure in the pipelines, but in mining operations this could then be fresh water or oil. A change in the current design would then be necessary.

Hydraulic pumps could be used for the dewatering of a mine, but there is a variety of pumps which can be chosen; external gear pump, internal gear pump, rotary vane pump, swash plate piston pump, radial pump and a hand pump. Each type of pump has advantages and disadvantages.

The efficiency of hydraulic pumping is important to know how much pressure is needed. In the best possible solution, all the hydraulic pressure is converted to a pumping motion. This is impossible, as there are always losses. For hydraulic systems, the efficiency is higher than a generator. Figure 9 gives an impression of the efficiency for a hydraulic pump related to the pressure of the hydraulic fluid.

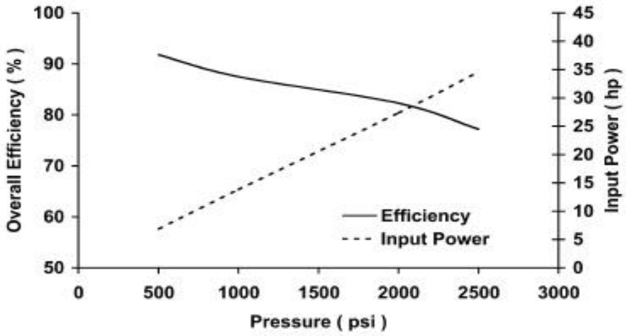


*Figure 9. Overall efficiency for a hydraulic pump driven at 1200 rpm. (Jack, 2009)*

For a pump running at 1200 rpm, the efficiency runs from approximately 75 to 90 percent. Figure 10 shows the efficiency of a diesel generator. The figure shows the power output in relation to the fuel consumption. The overall conclusion is that the total efficiency is very low, below 40%. Even when the output is 100%, the efficiency will not be higher than 35%.

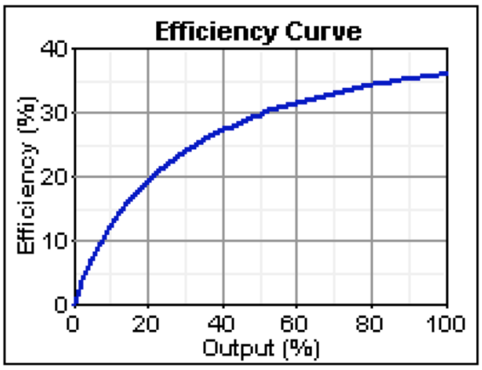


*Figure 10. Overall efficiency for a diesel generator. (Stiel & Skyllas-Kazacos, 2012)*

Since the efficiency is low, evaluating the fuel price is important. As more fuel is needed to reach a higher output, higher fuel prices will increase the overall price of electricity. The DOT concept does not need any form of fuel that is dependent on the market price; the wind is free.

## 4.3 Hydraulic system

Much mining equipment uses hydraulic pressure to function. As with mine dewatering, electricity is the premier method of supplying energy, in other words: an internal network of pressurized fluids. In current mines, there are a lot of moving parts which are driven by electric motors. This could also be done with a hydraulic motor. Stationary equipment can be connected to this internal network, whereas moving equipment cannot.

In mining operations, most of the equipment uses rotational motion in the form of a motor. For example, the processes that consume most of the mining energy are the milling and grinding processes. If the motor is not connected to the grid, energy is generated with a generator. Fuel is then converted into electricity, which is in its turn converted into a rotational motion. The use of two conversions is ineffective.

With the help of the DOT-system, it is possible to create a hydraulic network with pressurized fluids that creates motion. For example, grinding, crushing and milling are huge energy consumers in a mine, which usually run 24/7. There are various hydraulic driven engines on the market which could be installed. Using hydraulic pressure, the costs for fossil fuels can be reduced.

The DOT can be used for creating this pressure using the pump in its nacelle. The pressure is built up in the nacelle and is then pumped down into the internal hydraulic network. It is necessary to place the turbine as close as possible to the source which needs the pressure, to avoid any loss in pressure due to long traveling distances as a result of friction factors. In chapter 5.9, more information can be found about this case.

Compared to electrical losses, a 300mm copper cable loses circa 0.17 kW/m (McGee, 2014). In one meter, water flowing at 20 m/s through a steel welded pipe loses circa 20 mbar. This means the losses in a pressure network are less than in an electrical network.

In general, hydraulic motors are considered efficient. Looking at the types of hydraulic pumps, six different types can be distinguished. These types all use hydraulic pressure and convert it into rotational movement. All the types have different minimum and maximal rotations per minute (rpm) and their maximum pressures are different. Also, their costs differ for maintenance. However, the most important factor is their efficiency. To give an overview of these and the values in the different categories, table 10 is given.

| **Type** | **Max Speed** | **Min Speed** | **Pressure range** | **Running Efficiency** | **Variable option** | **Duty** | **Cost** | **Flow Range** |
|---|---|---|---|---|---|---|---|---|
| | **RPM** | **RPM** | **bar** | **%** | **-** | **-** | **-** | **L/min** |
| Ext. Gear | 2500 | 500 | 0-200 | 80-90 | No | Light | Low | 5-500 |
| Int. Gear | 2500 | 500 | 0-200 | 70-85 | No | Light | Low | 5-750 |
| Gerotor | 350 | 25 | 0-200 | Fair | No | Light | Low | Low |
| Vane | 2000 | 200 | 0-200 | 80-95 | Yes | Light | Medium | 5-300 |
| Axial | 12000 | 100 | 0-400 | 90-98 | yes | Heavy | High | 5-750 |
| Radial | 12000 | 0 | 0-400 | 85-95 | Yes | Heavy | Medium | 5-750 |

*Table 10. Overview of different hydraulic motor types. (Jack, 2009)*

As mentioned, there are lots of different motors that can be used with hydraulic pressure. For mining conditions, a motor is necessary that has a high efficiency, is suitable for heavyweight machines and whose costs are not exorbitant. Depending on the type of equipment, a motor with sufficient flow range to make sure it can carry out all the desired activities is selected. Considering the application of an internal hydraulic network, where a combination of two of the same pumps is needed, the internal and external gear motor can be used for lightweight duty, but for the heavy weight jobs, an axial or radial pump is needed, because of their high efficiency, high pressure range and a high maximum speed. The geroter should not be considered because its efficiency is unclear, noted as 'fair' in the overview. The vane motor is not applicable because it is suitable for light duty, but at a medium cost.

## 4.4 Electricity

A third way to apply the DOT type wind turbine is generating electricity. This is done by making offshore wind a competitive source of energy by reducing complexity, mass, required maintenance and the capital costs. With this in mind a new transmission concept for wind farms has been developed. For a schematic overview of the DOT-concept, see figure 8.

The main advantage of the DOT is the high power to weight ratio, which leads to weight improvements, which poses less burden on the construction. Furthermore, there are lower maintenance costs; there no gearboxes, generators and other expensive parts in the nacelle, which often require much maintenance. The absence of these parts make sure that incidents related to those parts cannot happen. In figure 11, it can be seen that, for example, electrics and gearbox issues are not possible anymore. Also the hydraulic components of the DOT have a much higher reliability than electrical ones.

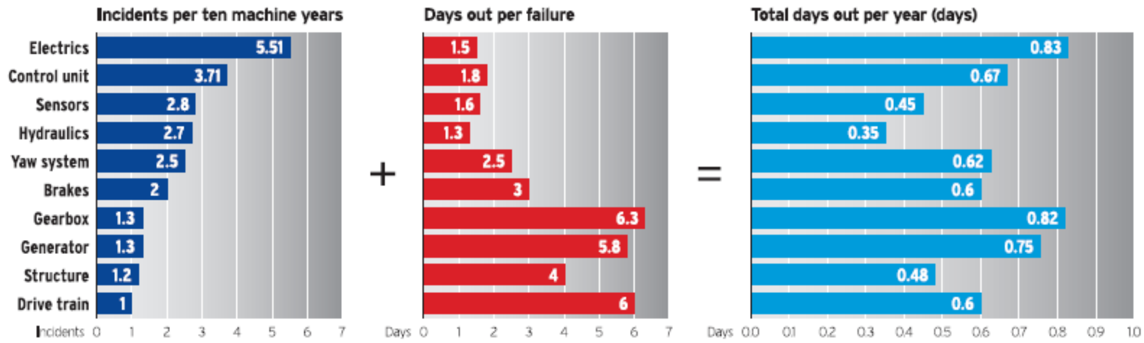


*Figure 11. Failure rates and outage time of wind turbine components (ISET, 2008).*

Figure 8 shows a DOT driven by seawater that is pumped under high pressure. When using the DOT in onshore mining areas, seawater is not available. Therefore, other fluids can be used, such as fresh water or oil. They can produce around 400 bars per unit (Diepeveen, 2012). Especially in onshore conditions the maintenance costs are not high, as there is easy access to the hydraulic generator. In offshore cases, a boat or platform is needed to go up to the nacelle, which brings significant costs.

Using hydraulic pumps, a high efficiency can be reached. Looking at tests, which have been carried out with the current technology of the DOT, it can be concluded that the efficiency is high compared to generators using fossil fuels. A MicroDOT test has been carried out with a 10-kV version, of which the results are presented in figures 12 and 13.

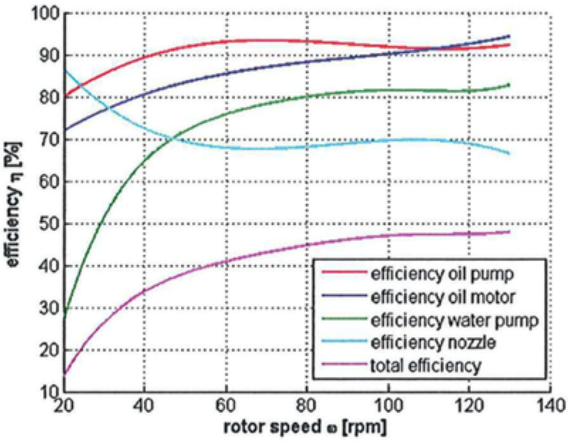


*Figure 12. MicroDOT of 10-kV efficiency curve. (Diepeveen, Jarquin Laguna, & Kempenaar, 2012)*

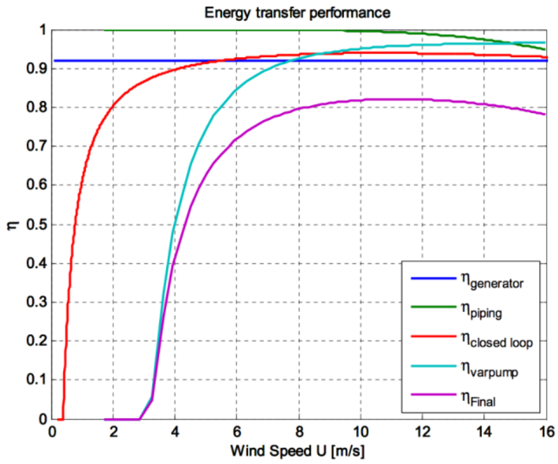


*Figure 13. Energy transfer performance for the DOT.*

For both efficiency curves, it is clear that under conditions of a wind speed of 10 m/s and a rotor speed of around 80 rpm, efficiencies of approximately 80% can be achieved. Comparing this to other general wind turbines, this is higher than average. The maximal efficiency that can be achieved is around 59%, also known as the Betz limit.

# 5 Opportune mining regions for the DOT

To carry out a trial with the DOT, a suitable location must be found. This is influenced by the feasibility for the placement of a foundation for the DOT, and what type of mine is available. Most important, however, is the average wind speed; after all no wind, no energy. Therefore, research has been carried out to evaluate the average wind speeds at different mining locations. Further, soil conditions have an influence on the placement of the DOT, because of differences in stability. If the ground condition is not suitable for heavy structures, the placement of wind turbines is not feasible at all. For every evaluated location, a table with different parameters is presented with a corresponding score, where 1 is worse and 5 is good.

To obtain a good overview, different maps have been overlaid in order to find the correct locations for mining activities. Quantum-GIS was used to georeference several maps in order to make them fit over each other. Figure 14 depicts the combined maps of different mining activities and the average wind speed at 80 meters high, which is a good approximation of the height of the DOT.

Multiple areas can be pointed out which could be suitable locations. These are evaluated in the next paragraphs. Areas with very low average wind speeds can be excluded immediately, because of their low efficiency.

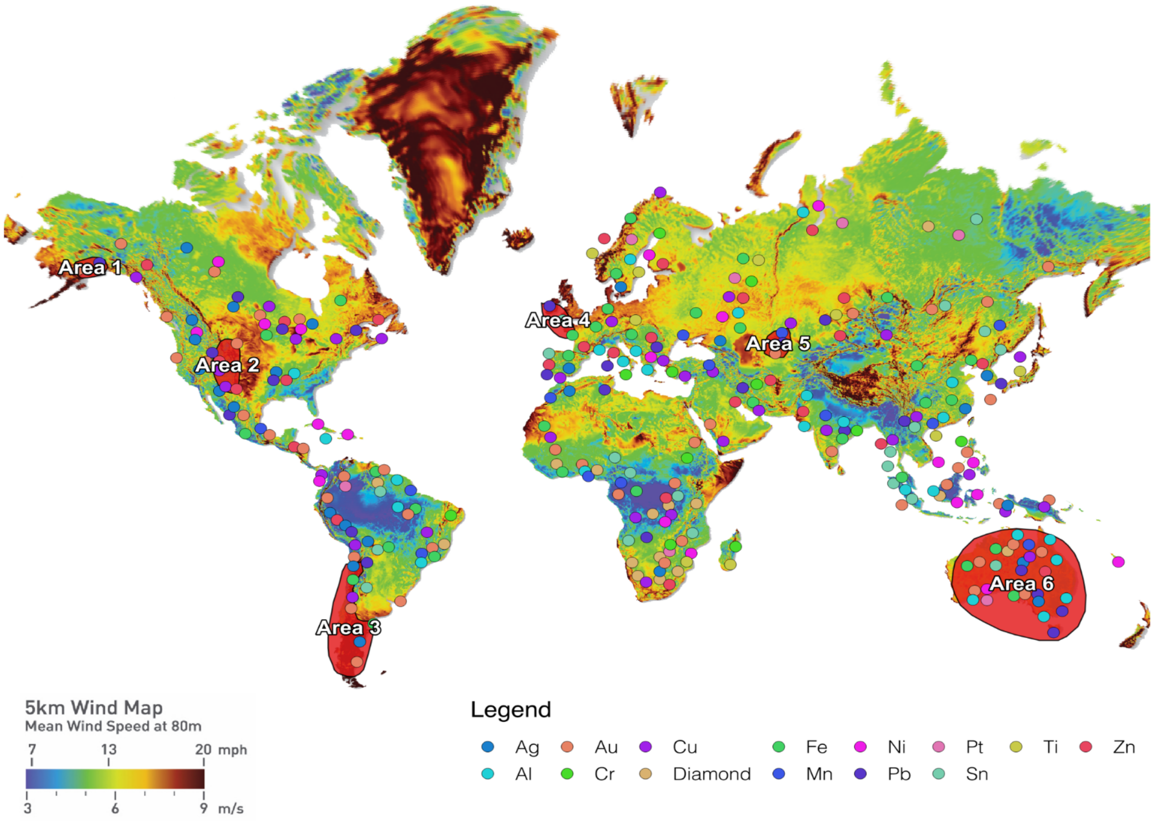


*Figure 14. Overview of mean wind speeds at 80-meter-high and mining locations around the world.*

For the evaluation, six areas have been chosen. In these areas, the average wind speeds are moderate to high. For these areas, see figure 14.

1. South Alaska (USA)
2. Central America
3. South Argentina and Chile
4. South England and North-East France
5. Central Asia (Kazakhstan and Uzbekistan)
6. Australia

Next, these areas are evaluated for the feasibility of the DOT-applications, regarding different facets. There are different requirements for surface and underground mining. Most important is the foundation of the turbine structure. For onshore mining operations, foundations are needed to create a safe situation for construction. The higher a turbine is placed, the more wind is available, but the more height, the higher the mean wind speed the turbine has to handle. These higher wind speeds cause significantly higher wind pressure on the nacelle than wind loads lower on the construction. Loads acting directly on the tower, acting on the nacelle, the blades and the nose have to be taken into consideration during construction. The turbine must hold its own weight, the torsional moment of the tower, and post-tensioning loads.

Knowledge about the soil at the mining location is needed in order to establish the necessary foundation thickness. This could reveal that a mining area is not suitable due to the need of a very thick, expensive foundation. Likewise, investigation could reveal stiff soil, which would necessitate a thinner foundation, which reduces the costs.

## 5.1 South Alaska

Alaska is a rural and remote place. The southern part has, on average a wind speed of circa 6.5 meters per second, which means it is a good possible location for a wind farm (Archer & Jacobson , 2005). According to the map of global mining locations, a gold and lead mine are located in this area.

Ground conditions are good; the soil consists of Quaternary deposits, Tertiary sedimentary and Mesozoic metamorphic and volcanic rocks, which are usually very hard and suitable for lightweight foundations, which reduces costs (USGS, 2017).

The elevation is not a problem. Most of the area is between 500 and 1500 meters above sea level, which is an advantage for wind turbines (ESRI, 2017). Downsides of this area could be the cold environment. Also, it is a relatively small area to test the DOT.

The low temperatures could be a problem, using wind turbines. Not all turbines can withstand very low temperatures. With an average below zero, it is likely there are also extreme cold periods, which can make it difficult to let the turbine work.

| Parameter | Value | Unit | Score |
|---|---|---|---|
| Wind speed | 5.9 – 6.9 | m/s | 3 |
| Soil condition | Mostly Hard | - | 5 |
| Elevation | 500 – 1500<br>*Lots of peaks* | m | 2 |
| Temperature | -5.35 | °C | 1 |
| Mining activity | 2 | mines | 2 |
| | | *Total score:* | *13* |

*Table 11. Different parameters and corresponding scores for South Alaska.*

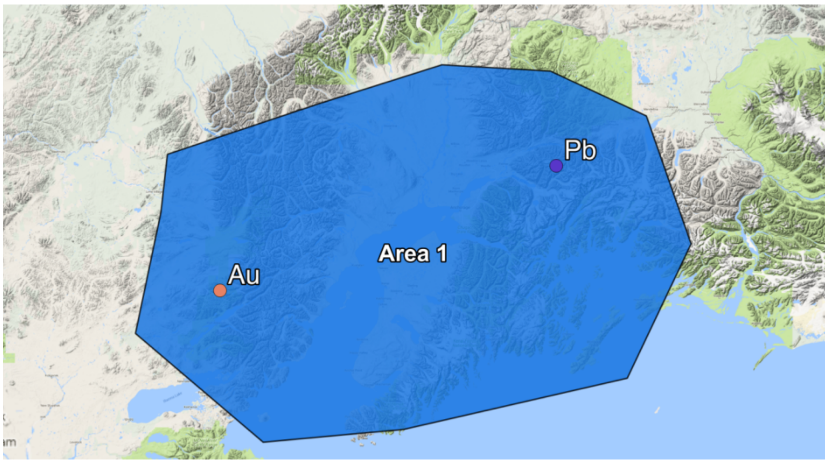


*Figure 15. Schematic area of interest in South Alaska*

## 5.2 Central America

Central America should also be considered as a test location for the DOT. The average wind speed is around a mean of 7 to 7.5 meters per second (Archer & Jacobson , 2005). In figure 16, several mining operations can be seen, including gold, zinc, and copper mines.

However, it is unclear if those are located underground or on the surface. The mines are located in an inhabited area, so perhaps infrastructure has to be created (ASCE, 2017). The majority of the soil consists out of sandstones, shales and conglomerates with intrusions of metamorphic rocks. Therefore, the soil is suitable for building lightweight foundations (USGS, 2017).

Disadvantages for this location can be found when looking at the elevation. It can be mentioned that the area is mountainous, because it is located near multiple mountain ranges with moderate slopes which can also have very inclined variants (ESRI, 2017). The construction of the wind turbines can therefore be tough, and the area could even be unsuitable to build large wind farms.

| Parameter | Value | Unit | Score |
|---|---|---|---|
| Wind speed | 6.9 – 7.5 | m/s | 3 |
| Soil condition | Mostly hard | - | 5 |
| Elevation | 1900 – 2800<br>*Mainly flat, some peaks* | m | 3 |
| Temperature | 8.55 | °C | 4 |
| Mining activity | 5 | mines | 3 |
|  |  | *Total score:* | *18* |

Table 12. Different parameters and corresponding scores for Central USA.

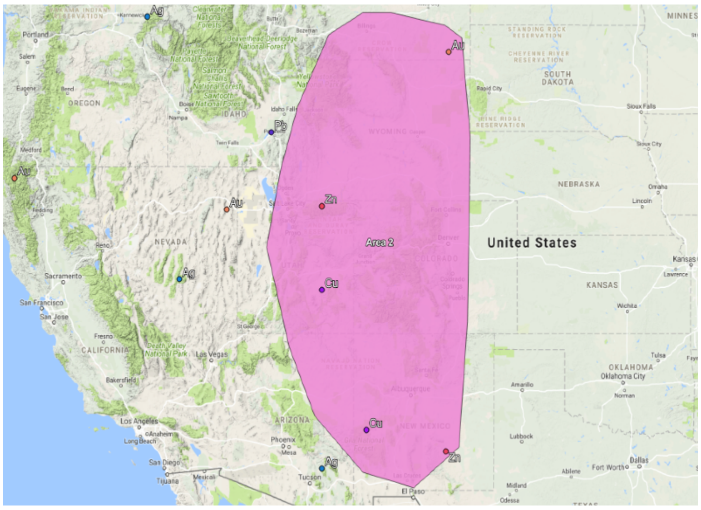


Figure 16. Area of interest in Central USA

## 5.3 South Argentina and Chile

Approaching a different continent, South Argentina and Chile are options to evaluate the possibility of a wind farm using the DOT. Especially in the southern region, the use of wind energy is not common, due to a lack of wind farms (GWE, 2016).

Average wind speeds are high, with outliers of 9 to 10 meters per second, which makes it one of the regions of interest with the highest average wind speed at 80 meters above ground level. Especially coastal environments located near the South Pole give higher wind speeds. The geology for both South Argentina and Chile are almost the same. Sedimentary Quaternary rocks are interspersed with volcanic rocks from Quaternary, Cretaceous and the Mesozoic (ANDGEO, 2017).

However, when evaluating relief and elevation maps, the mountain ranges between Chile and Argentina are immense. Height can add up to 3000 meters and the western part of Chile and can definitely not be used for the construction of a proper wind farm (ESRI, 2017).

Looking at the eastern part of Southern Argentina, it could be possible. It is quite high, but the relief is moderate, from 0 meters at the coast to 500 meters more land inwards. Different sorts of mining are active in the region, with main elements such as gold, silver, iron and copper.

| Parameter | Value | Unit | Score |
|---|---|---|---|
| Wind speed | 7.5 – 8.1 | m/s | 4 |
| Soil condition | Various | - | 2 |
| Elevation | 500 – 800<br>*Chile: Some high peaks*<br>*Argentina: Mostly flat* | m | 3 |
| Temperature | 8.45 - 14.8 | °C | 4 |
| Mining activity | 7 | mines | 4 |
| | | *Total score:* | *17* |

*Table 13. Different parameters and corresponding scores for South Argentina and Chile.*

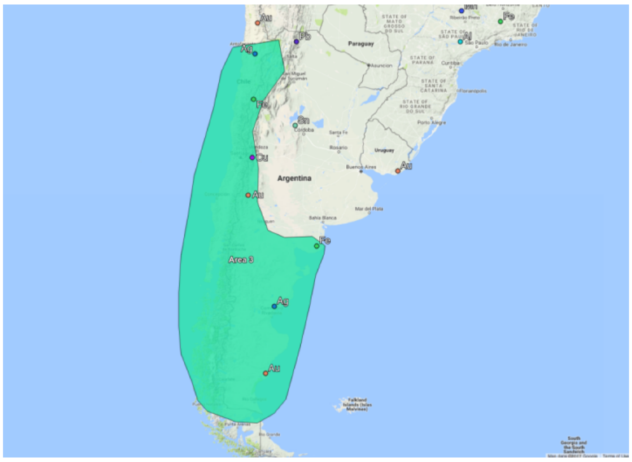


*Figure 17. Area of interest in Chile and Argentina*

## 5.4 South England and North-East France

For evaluating a future project in Europe, Ireland, South England and France have been selected because of their high average wind speeds in combination with some possible locations. Here wind speeds have values of circa 9 meters per second (Archer & Jacobson , 2005).

Lead, zinc and iron mines are located in the three different countries. In England, the south-west coast consists out of intrusive rocks which are mainly granite, which is very hard. Only in south-west England, some hills can be distinguished, but these would not be a major issue.

The elevation is flat, the height differ between 100 and 200 meters, with some peaks which would be not a problem (ESRI. 2017).

| Parameter | Value | Unit | Score |
|---|---|---|---|
| Wind speed | 8.6 – 9.4 | m/s | 5 |
| Soil condition | Mostly soft | - | 3 |
| Elevation | 100 – 200 m<br>*Mostly flat* | m | 4 |
| Temperature | 8.45 – 10.70 | °C | 4 |
| Mining activity | 3 | mines | 1 |
|  |  | *Total score:* | *17* |

Table 14. Different parameters and corresponding scores for South England and North-East France.

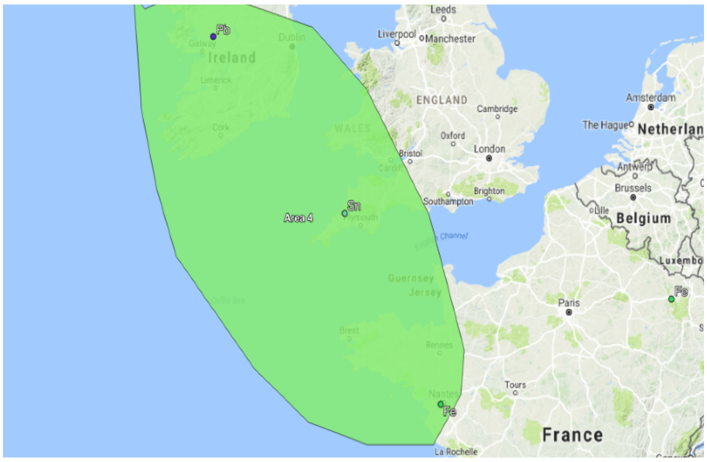


Figure 18. Area of interest in England and France

## 5.5 Central Asia (Kazakhstan and Uzbekistan)

Focusing on onshore energy mining solutions in Central Asia is challenging. Both Kazakhstan and Uzbekistan have minimal or no wind farms (GWE, 2016). The elevation is in excellent condition for wind farms; there are great plains where high wind speeds should be expected. However, wind speeds are measured around a mean of 5 to 6 meters per second (Archer & Jacobson , 2005).

The soil consists of sedimentary structures (Visser, 2007). In Kazakhstan, there is a manganese and lead mine; in Uzbekistan a gold mine is in production. It could also be a good thing to produce green energy in this area, as they have the reputation of causing a lot of pollution.

| Parameter | Value | Unit | Score |
|---|---|---|---|
| Wind speed | 4.9 - 5.9 | m/s | 2 |
| Soil condition | Mostly soft | - | 3 |
| Elevation | 50 – 110<br>*Mostly flat* | m | 5 |
| Temperature | 6.40 – 12.05 | °C | 4 |
| Mining activity | 3 | mines | 1 |
|  |  | *Total score:* | *15* |

Table 15. Different parameters and corresponding scores for Central Asia.

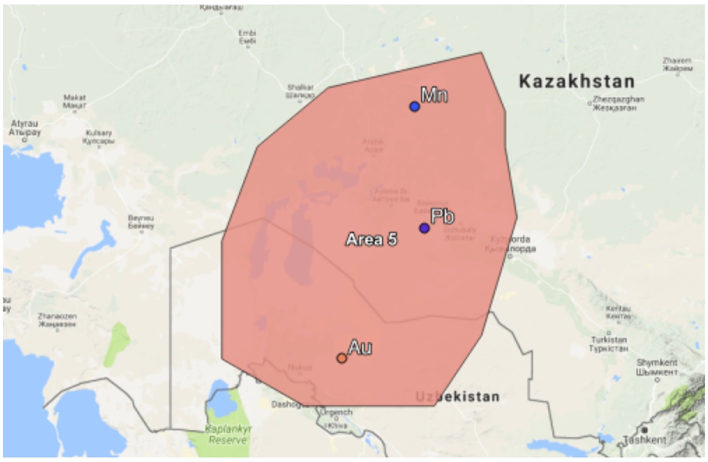


Figure 19. Area of interest in Kazakhstan and Uzbekistan

## 5.6 Australia

Australia is known for its activity in mining; in the field of wind turbines they are also growing, especially in the south-eastern part of the country. Figure 20 makes clear that Australia has a lot of mining activity, with main elements such as gold, nickel, iron, aluminium (bauxite), platinum, lead, copper, diamonds, zinc, silver and tin.

Looking at the average wind speed, especially in the coastal areas, excepting the north coast, the placement of turbines is feasible. Wind speeds from six to ten meters per second are measured. Further north, the wind speeds lower to around six meters per second (Archer & Jacobson , 2005). The variety in the geology is enormous, which makes it difficult to make an overall decision (Raimondo, 2017).

However, it should be possible to find the ideal foundation for the potential wind turbine. Looking at the map reveals that there are some places where the ground is elevated (ESRI, 2017), but it is possible to place wind turbines. This, in combination with a good reliability and infrastructure, and the reputation of mining in this country, it is likely to find a good test location somewhere in the south-eastern part of Australia.

| Parameter | Value | Unit | Score |
|---|---|---|---|
| Wind speed | 6.1 – 10.6 | m/s | 5 |
| Soil condition | Various | - | 3 |
| Elevation | 50 - 250<br>*Mainly flat* | m | 4 |
| Temperature | 21.65 | °C | 5 |
| Mining activity | > 20 | mines | 5 |
|  |  | Total score: | 22 |

Table 16. Different parameters and corresponding scores for Australia.

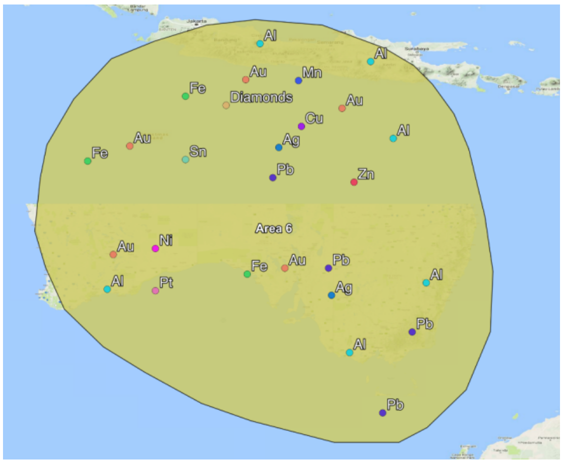


Figure 20. Area of interest in Australia

## 5.7 Summary

Making a good estimation of the potential of the locations mentioned above, a small case study has to be developed to know if a system like the internal hydraulic network could work. Of course, the average wind speed, soil, elevation and activity are important. Therefore, from the six different areas, one area is chosen for carrying out a case study. These choices are based upon the average wind speed at 80 meters above ground level, the soil conditions, the elevation of the area and mining activity. In table 17 a summary is given, with the scores of these options; where a one is the lowest score and a five the highest.

| Area | Wind speed | Soil condition | Elevation | Temperature | Activity | Score |
|---|---|---|---|---|---|---|
| South Alaska | 3 | 5 | 2 | 1 | 2 | **13** |
| Central America | 3 | 5 | 3 | 4 | 3 | **18** |
| South Argentina and Chile | 4 | 2 | 3 | 4 | 4 | **17** |
| South England and North-East France | 5 | 3 | 4 | 4 | 1 | **17** |
| Central Asia (Kazakhstan and Uzbekistan) | 2 | 3 | 5 | 4 | 1 | **15** |
| Australia | 5 | 3 | 4 | 5 | 5 | **22** |

*Table 17. Different areas with corresponding scores.*

According to the table, Australia has the highest score. Most important is wind speed in combination with the mining activity in that area. If the test is run in an area where there are lots of mines with similar conditions, it could be interesting to see if those projects are possible in other locations. Australia has multiple mines which are also active in different sectors. Central America is also feasible due to high average wind speeds throughout the year, but a downside here is that there are differences in the elevation, which can cause problems when constructing the DOT.

# 6 Economic and ecological impact using simulated case studies

## 6.1 Introduction

According to the previous chapter, Australia should be a good location for testing the DOT in mining applications. Mining has been present in Australia for centuries. Many mines, active in several minerals, are operational today. This activity uses a lot of energy. According to the energy statistics of Australia for the year 2016, 520.7 PJ (petajoule) is consumed by mining operations, which is equal to 8.8% of the total consumption of Australian industries. Table 18 shows how this use is split; the oil and gas industry have the biggest share, as does coal mining, which is smaller than the share of the "Other mining" category.

It is logical to choose the DOT testing mine in the category "Other mining". Even though the oil and gas category uses a larger portion of the energy, and therefore may seem a logical choice for the test site, it would be hard to use the DOT there, because most of the industry is situated offshore. Australia has no plans to expand their wind industry to offshore areas, as The Global Wind Report (2015) mentions: "All Australian wind farms are land-based and no proposals currently exist to develop an offshore industry." Therefore, onshore use of the DOT in mining activities is preferred. In the future, the DOT could be used in those areas, but for the development it is easier to start with an onshore location, hence the choice for the second largest energy consumer: "other mining".

Noteworthy is that the annual growth of electricity consumption is negative for the first time in ten years. This is also caused by the use of alternative energy sources in the mining industries, which leads us to believe the mining industry in Australia would be open to a new alternative energy source.

| | 2014-2015 | | Average annual growth | |
|---|---|---|---|---|
| | PJ | Share (%) | 2014-15 (%) | 10 years (%) |
| Oil and gas | 215.1 | 41.3 | -0.5 | 4.4 |
| Coal | 125.8 | 24.2 | -4.1 | 5.5 |
| Other mining | 179.8 | 34.5 | -2.2 | 8.7 |
| **Total** | **520.7** | **100.0** | **-2.0** | **6.0** |

*Table 18. Australian mining energy consumption. (Australian Government, 2016)*

Not all areas in Australia are suitable for usage, due to different wind velocities. An evaluation is needed to decide which area is best suitable for the usage of wind energy. For simplification, Australia is split into seven parts, which in general, are the states, except for Victoria and New South Wales, which have been combined to one area, and Western Australia, which has been split. This is done due to the size of Western Australia in combination with the differences in wind speed between the north and the south of this state. It also good to evaluate the north and south separately, because most of the off-grid mining operations are found in Western Australia.

## 6.2 Methodology

To evaluate the wind speeds of these regions, the data for the average wind speeds per month, collected over circa 40 years, is used. Three different weather stations are used, which are all close to an active mine in the chosen area, although the measured wind speed is not at the height of the nacelle. To extrapolate the wind speed to the desired height, the log law for wind speed extrapolation is used (Johnson, 1999).

$$v \approx v_{ref} * \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

Where: $v$ = velocity to be calculated at height $z$

$v_{ref}$ = known velocity at height $z_{ref}$

$z$ = height above ground level for velocity $v$

$z_{ref}$ = reference height where $v_{ref}$ is known

$z_0$ = roughness length in the current wind direction

This expression can be used in the lowest 100 meters of extrapolation, which makes it sufficient to use for the height of the nacelle. The roughness length in the current wind directions is a constant related to the type of landscape. Table 19 shows the different roughness classes with the corresponding roughness length in meters and the landscape type. For the case study, it is assumed that the mines are located in a remote area where there are no large buildings and no cities. The different values for the roughness lead to the so-called multiplication factor, which is used to multiply the speed at the known altitude. From the above equation, the multiplication factor can be described as;

$$multiplication\ factor \approx \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

The variables have the same parameters as the formula above. Here, the referential height is chosen at four meters. Because no data is available for the height of the measurement, this height is assumed. The height above ground level to extrapolate the velocity, is determined to be 80 meters. As mentioned, the multiplication factor varies with the roughness class and the corresponding roughness length, which are linked to the landscape type of the area. To evaluate the possible multiplication factor for reference height at four meters and the height of 80 meters, figure 21 gives an overview of the factors and their roughness class.

For the general cases in Australia, it can be assumed that roughness class 1 can be applied, since the corresponding landscape type, according to the literature, is defined as followed: “Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills” (EWA, 2017). This fits well with the expected terrain in the area of the mines in the regions. If a higher roughness class would be used, the extrapolated wind speeds would increase even more, as seen in figure 21. The power produced by the wind turbine is calculated with the following formula;

$$P = \frac{1}{8} * C_p * \rho * \pi * d^2 * v^3$$

Where $C_p$ is the efficiency related to the turbine,
$\rho$ is the density of air
d is the diameter of the wind turbine area,
v is the velocity of the wind and
P is the power in watt.

| Roughness Class | Length (m) | Landscape Type |
|---|---|---|
| 0 | 0.0002 | Water surface |
| 0.2 | 0.0005 | Inlet water |
| 0.5 | 0.0024 | Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc. |
| 1 | 0.03 | Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills |
| 1.5 | 0.055 | Agricultural land with some houses and 8-metre-tall sheltering hedgerows with a distance of approximately 1250 metres |
| 2 | 0.1 | Agricultural land with some houses and 8-metre-tall sheltering hedgerows with a distance of approximately 500 metres |
| 2.5 | 0.2 | Agricultural land with many houses, shrubs and plants, or 8-metre-tall sheltering hedgerows with a distance of approximately 250 metres |
| 3 | 0.4 | Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain |
| 3.5 | 0.8 | Larger cities with tall buildings |
| 4 | 1.6 | Very large cities with tall buildings and skyscrapers |

*Table 19. Roughness definitions according to the European Wind Atlas. (EWA, 2017)*

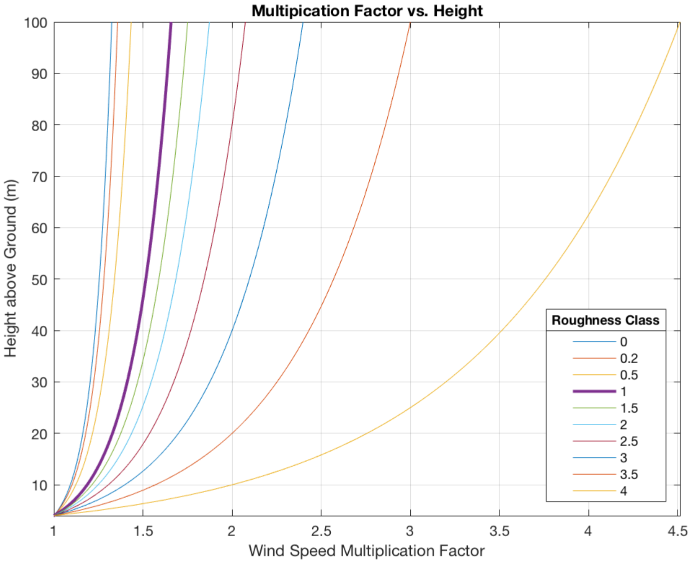


*Figure 21. Multiplication factor versus the extrapolated height, with the thick line presenting the chosen multiplication factor for this case.*

## 6.3 Mining Activity

Figure 22 shows a map of all the operating mines in 2010. The majority of the mines are in Western Australia or in the east of Queensland, but also in the southeast several mines are found. Combining this image with figure 23, regions can be determined where there are only gas pipelines available or where neither gas nor electricity (pipe) lines are available. Especially those areas are interesting for usage of the DOT. The following paragraphs give a concise discussion of the average wind speeds throughout the year and the corresponding power that could be generated with those average wind speeds.

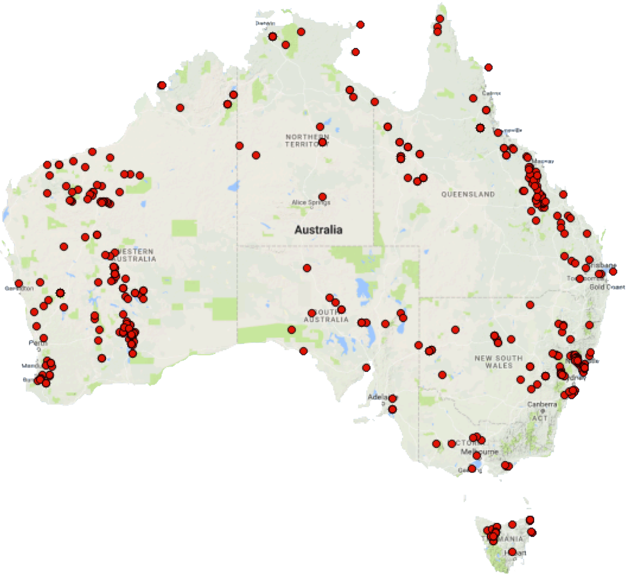


*Figure 22. Map of mining locations in Australia in 2010. (Australian Government, 2016)*

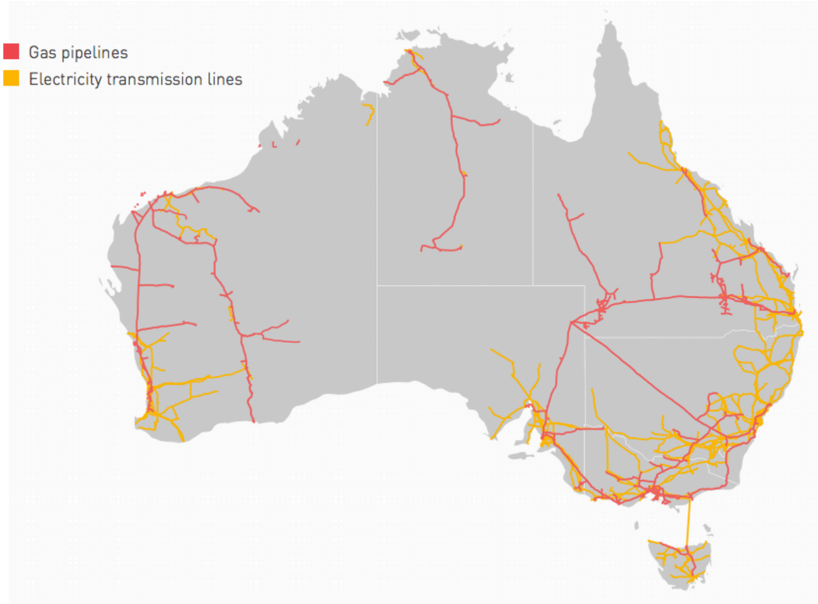


*Figure 23. Australia's electricity transmission lines and onshore gas pipeline infrastructure (National Online Gas Pipeline Database, 2017)*

### 6.3.1 Western Australia (Northern Part)

As can be seen in figure 24, there is a lot of mining activity in the Northern Part of Western Australia. Therefore, it would be considerable to implement the DOT. Evaluating the wind speed and power, the amount that could be generated is reasonable, with an average output around 0.7 MW per wind turbine. The differences in wind speeds between 3 a.m. and 9 p.m. are not much, and also the fluctuations between the months are not really large, which is a positive contributor to having an almost constant supply of energy.

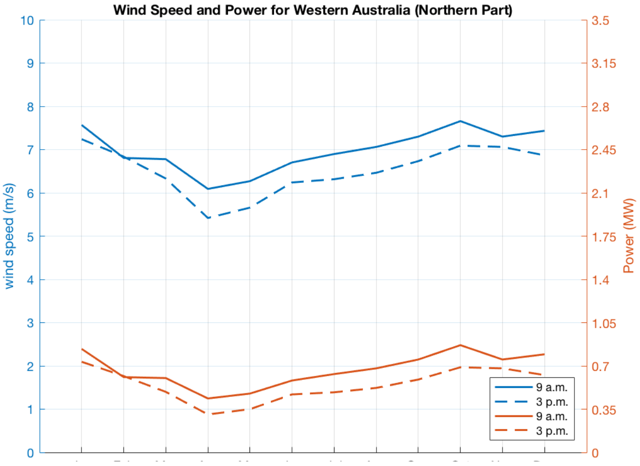


*Figure 24. Average wind speed versus power output for Western Australia (North). (Bureau of Meterology, 2017)*

### 6.3.2 Western Australia (Southern Part)

As can be seen in figure 25, there is a lot of mining activity in the southern part of Western Australia, so this area could also be considered as a testing area of the DOT. Evaluating the wind speed and power, the amount that could be generated is reasonable and comparable with the northern part, with an average output that is also around 0.7 MW per wind turbine. The differences between 3 a.m. and 9 p.m. however, are significant, and the variation between the months is also worth mentioning. The difference can be more than 2 m/s, which is negative for the continuous wind speed. Therefore, the southern part is less suitable than the northern part of Western Australia.

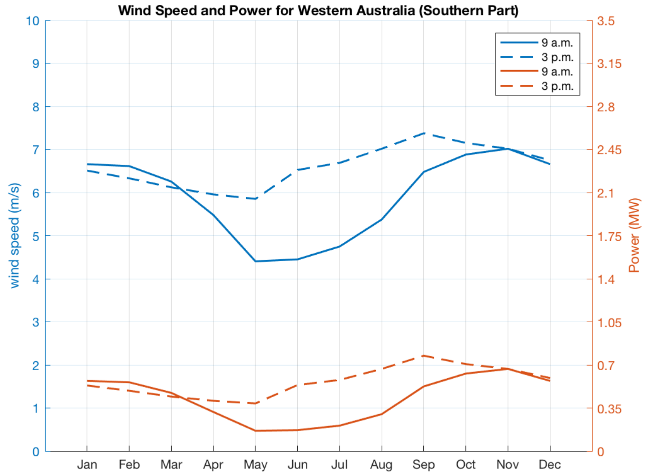


*Figure 25. Average wind speed versus power output for Western Australia (South). (Bureau of Meterology, 2017)*

### 6.3.3 Tasmania

As can be seen in figure 26, there is a lot of mining activity in a relatively small area, compared to the rest of the regions. Implementing the DOT here could be considered, because the turbines could be linked to multiple mines in the area. Evaluating the wind speed and power, the amount that could be generated is high, with an average output between 0.4 and 1.1 MW per wind turbine. However, the differences between 3 a.m. and 9 p.m. are large, which can be linked to the fact that is in an island at the most southern part of Australia, and therefore sensitive to wind fluctuations.

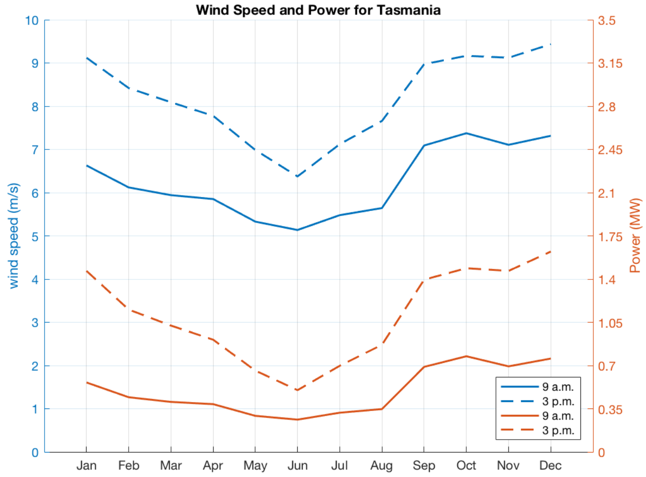


*Figure 26. Average wind speed versus power output for Tasmania. (Bureau of Meterology, 2017)*

### 6.3.4 New South Wales and Victoria

Mining activity is also seen in New South Wales and Victoria, especially around the coastal areas. Therefore, it would be interesting to consider the option. However, these mines are mostly coal mines, which are not the main target of the DOT. Instead, a more remote area with mineral mining is preferred. Looking at the wind speed and power, the amount that could be generated is reasonable, with an average output around 0.7 MW per wind turbine. The differences between 3 a.m. and 9 p.m. are not large, but the fluctuations in the months could be a problem in maintaining a continuous supply of energy. Therefore, the testing of the DOT is not feasible in this region.

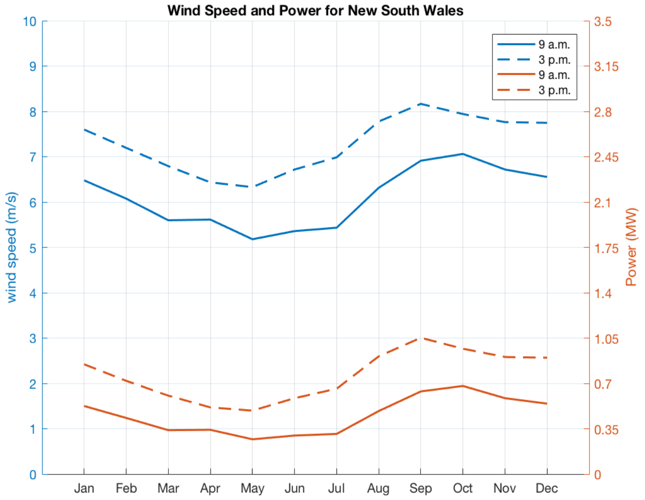


*Figure 27. Average wind speed versus power output for New South Wales and Victoria. (Bureau of Meterology, 2017)*

### 6.3.5 Queensland

As can be seen in figure 28, there is a lot of mining activity in the north-eastern part of Queensland, which are almost all coal mines. As mentioned in the review of New South Wales and Victoria, this is not the DOT's target industry. Evaluating the wind speed and power, the amount that could be generated is low, with an average output around 0.4 MW per wind turbine. However, Queensland is not suitable for the usage of the DOT, because of its coal mines.

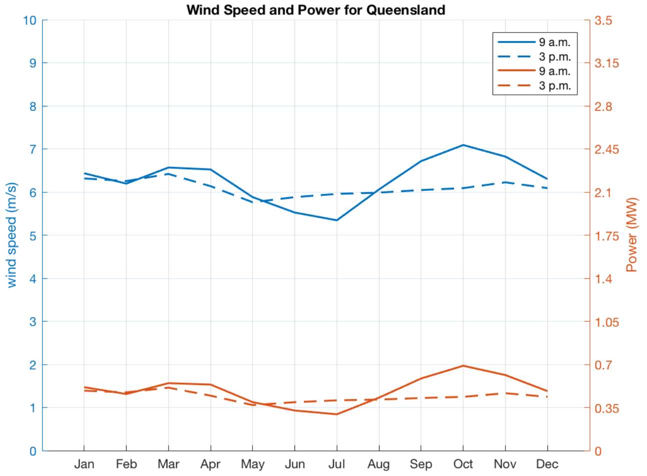


*Figure 28. Average wind speed versus power output for Queensland. (Bureau of Meterology, 2017)*

### 6.3.6 South Australia

As can be seen in figure 29, there are not many mines in South Australia. Therefore, the region does not seem feasible for the application of the DOT. Looking at the wind speed and power, the amount that could be generated is low, with an average output between 0.1 and 0.6 MW per wind turbine. The differences between 3 a.m. and 9 p.m. are also high, and the fluctuations in the months could be a problem to maintain a continuous supply of energy. Therefore, the testing of the DOT is not feasible in this part of Australia.

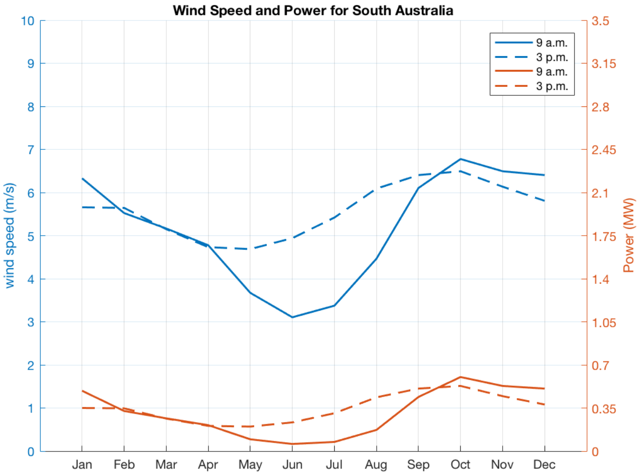


*Figure 29. Average wind speed versus power output for South Australia. (Bureau of Meterology, 2017)*

### 6.3.7 Northern Territories

As can be seen in figure 30, there are only thirteen mining sites in the Northern Territories. Most of these mines are located in coastal areas, where usually a connection to the grid is available. Therefore, this area is not interesting to consider. Furthermore, looking at the wind speed and power, the amount that could be generated is low, with an average output between 0.2 and 0.7 MW per wind turbine. The differences between 3 a.m. and 9 p.m. are not large, but fluctuations between months could be a problem to maintain a continuous supply of energy. Mainly because of the low mining activity, the Northern Territories are not a suitable place to consider the usage of the DOT.

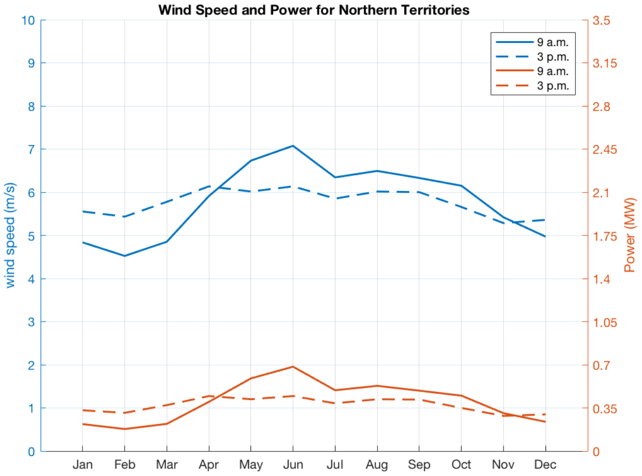


*Figure 30. Average wind speed versus power output for Northern Territories. (Bureau of Meterology, 2017)*

## 6.4 Distribution

The cases above mention only the average speeds for different months throughout periods of a maximum of 40 years. To calculate the chance that a certain wind speed occurs, daily data from 3 a.m. and 9 p.m. from one year was evaluated, from the first of July 2016 until the 30th of June 2017. First, the data is projected into a histogram to show the distribution of the wind speeds. Second, a normal probability density function is created to know the probability of a certain wind speed, which can be seen in figure 31.

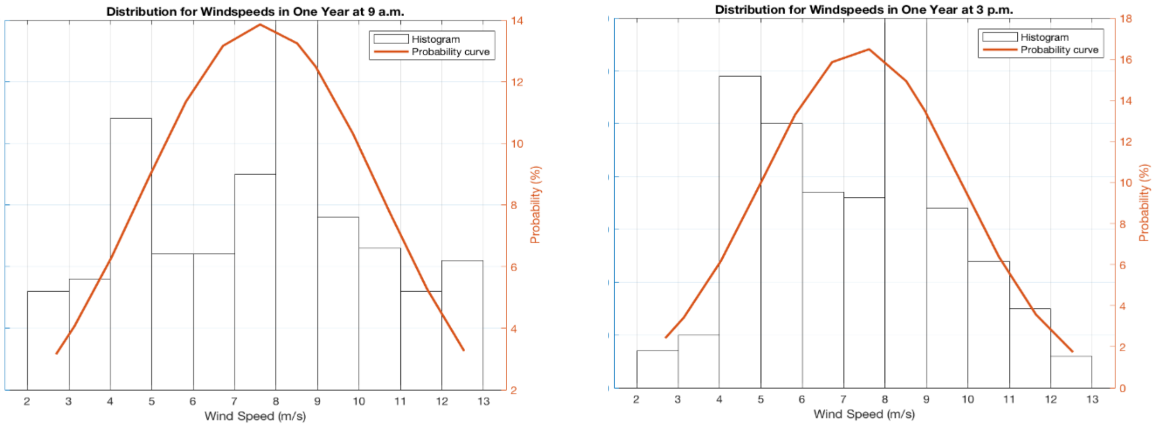


*Figure 31. Histograms and normal probability density functions for wind speeds throughout one year.*

The wind speeds per month are different. Per season, the wind speed also changes. Figure 32 shows the wind speeds per month with corresponding error bars. For each month $\mu$ and $\sigma$ are calculated. Assuming that wind speeds will not differ more than one $\sigma$, the error bars show the variance in wind speed one $\sigma$ above and below $\mu$. The corresponding confidence levels for $\mu$ vary between 5.0 and 8.1 percent and for $\sigma$, the values vary between 1.6 and 3.3 percent.

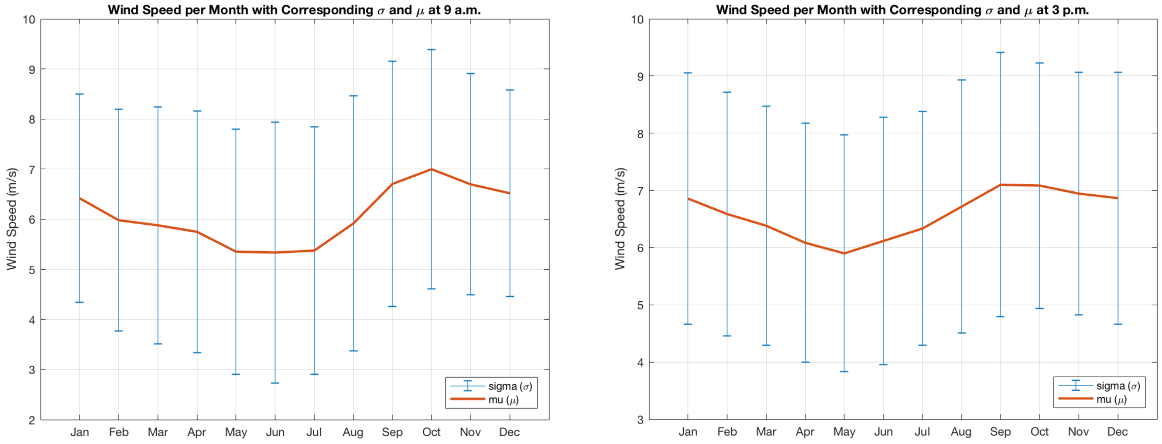


*Figure 32. Wind speeds per month with corresponding error bars.*

For the seasons, a ranking can be made for when the chances for a high wind are best. Discussing figure 32, September, October and November have the highest wind speeds. Looking at the error bars, the variances are also minimal. In Australia, these three months are defined as spring. From the used data, there were fourteen days with almost no wind, which means a chance of 4% that there is no available wind. If there is no wind, there is also no power output and generators will have to take over the energy generation.

The results are evaluated using the normal distribution. This states that circa 68.2% of the measurements are within one standard deviation. Circa 27.2% lies between one and two standard deviations, 4.2% between two and three standard deviations and 0.2% bigger than three standard deviations.

Table 20 and 21 give the parameters of $\sigma$ and $\mu$ for the wind speed and the output power obtained by using the standard deviation method. Table 21 and 23 give the possibilities and ranges for wind speeds and power output.

| Time | Wind speeds (m/s) | |
|---|---|---|
| | mu ($\mu$) | sigma ($\sigma$) |
| 9 a.m. | 7.6 | 2.9 |
| 3 p.m. | 7.4 | 2.4 |

*Table 20. Normal probability density function parameters for the wind speed.*

| Time | Possibilities | Minimum between | | Maximum between | |
|---|---|---|---|---|---|
| 9 a.m. | 68.2% | 4.7 | 7.6 | 7.6 | 10.5 |
| | 27.2% | 1.8 | 4.7 | 10.5 | 13.4 |
| | 4.2% | 0 | 1.8 | 13.4 | 16.3 |
| | 0.2% | 0 | 0 | 16.3 | >20 |
| 3 p.m. | 68.2% | 5.0 | 7.4 | 7.4 | 9.8 |
| | 27.2% | 2.6 | 5.0 | 9.8 | 12.2 |
| | 4.2% | 0.2 | 2.6 | 12.2 | 14.6 |
| | 0.2% | 0 | 0.2 | 14.6 | >20 |

*Table 21.Probabilities for wind speeds according to the normal distribution.*

| Time | Power Output (MW) | |
|---|---|---|
| | mu ($\mu$) | sigma ($\sigma$) |
| 9 a.m. | 1.04 | 0.70 |
| 3 p.m. | 0.94 | 0.68 |

*Table 22. Normal probability density function parameters for the power output.*

| Time | Possibilities | Minimum between | | Maximum between | |
|---|---|---|---|---|---|
| 9 a.m. | 68.2% | 0.34 | 1.04 | 1.04 | 1.74 |
| | 27.2% | 0 | 0.34 | 1.74 | 2.44 |
| | 4.2% | 0 | 0 | 2.44 | 3.14 |
| | 0.2% | 0 | 0 | 3.14 | >3.5 |
| 3 p.m. | 68.2% | 0.26 | 0.94 | 0.94 | 1.62 |
| | 27.2% | 0 | 0.26 | 1.62 | 2.30 |
| | 4.2% | 0 | 0 | 2.30 | 2.98 |
| | 0.2% | 0 | 0 | 2.98 | >3.5 |

*Table 23. Probabilities for power output according to the normal distribution.*

## 6.5 Best location

Looking at the best cases for usage of the applications of the DOT, the northern part of Western Australia and Tasmania could be good locations. For both, the average wind speeds are high and fluctuations can be overcome, especially in Tasmania where the wind speeds are so high they can compensate for the fluctuating velocities by installing batteries that store excess energy. The current development in the Australian energy sector is towards green energy. Table 24 shows the current amount of energy that is created by each state. From it, it becomes clear that Tasmania and Western Australia are behind compared to some other states. Therefore, it is interesting to expand the capacity in these areas.

| State | Installed Capacity (MW) |
|---|---|
| South Australia | 1,475 |
| Victoria | 1,230 |
| New South Wales | 668 |
| Western Australia | 491 |
| Tasmania | 310 |
| Queensland | 12.5 |
| Total | 4187 |

*Table 24. Installed wind power capacities in different regions of Australia (GWEC, Global Wind Report 2015).*

According to the Global Wind Report of 2015 (GWEC), these 4,187 MW are divided across 2,062 wind turbines which are located on 76 windfarms. The total energy that is supplied by windfarms is 5 percent of the country's total.

Considering the relatively low amount of capacity in Western Australia and Tasmania, there are chances for the usage of the DOT in those areas. According to the average wind speeds, the average power throughout the whole year will fluctuate between 0.5 and 1.5 MW per wind turbine. Here, higher wind gusts are not included. Therefore, the peaks in power could be higher, but a lack of wind, and therefore a lack in power is not inconceivable.

The feasibility of these projects is high. Australia is a significant energy consumer and is ready to increase its reliability on wind energy. Also, the people of Australia see the importance of using wind energy to replace fossil fuels. According to the Global Wind Report (2015); "The Clean Energy Council is expecting a big 2016 for the wind industry, with new projects signing deals and construction getting into full swing wind energy enjoys broad support across Australia, including in the regions in which wind farms are situated; and the newly-revised Renewable Energy Target will mean almost doubling the installed wind capacity in the next four years."

All in all, wind energy is widely carried by the habitants of Australia and is already used in all regions, on a big or small scale. In the future, the usage of the DOT could also be applied in all these regions, but maybe not for use in the mining industry. In that sector, focussing on regions in Western Australia and Tasmania would be better.

## 6.6 Comparison of costs for energy sources

The overall goal is to reduce costs and increase the generation of green energy. Using the DOT in a grid-connected area, the dependency of electricity can be reduced. It is estimated that the costs of electricity from the DOT is circa 30% cheaper than electricity produced by conventional wind turbines (Diepenveen, 2017). Comparing this with electricity generated with other fossil fuels, this is a big difference. In figure 33, an overview of those costs can be seen for Australia.

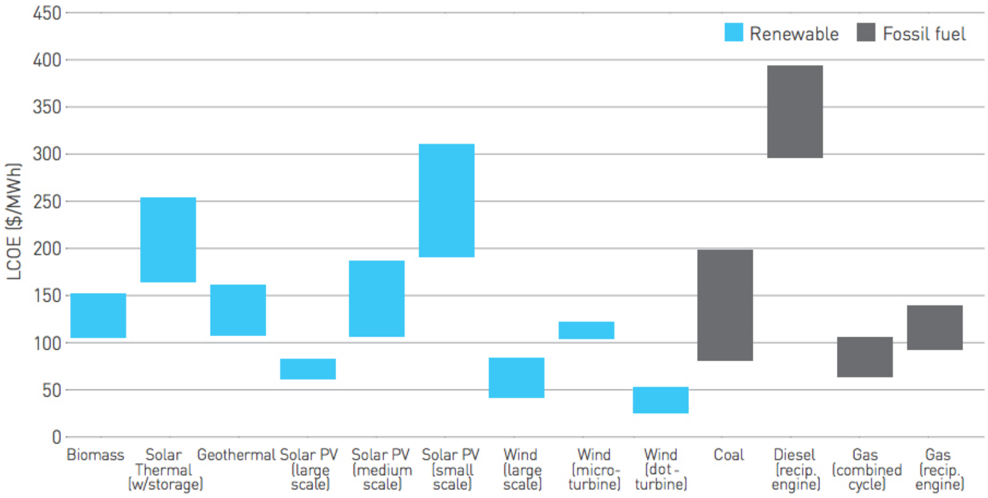


*Figure 33. The current unsubsidised levelled cost of electricity (LCOE) from fossil fuel and renewable sources. Modified to include the DOT turbine. (Australian Government, 2016)*

Here, wind energy on a large scale has an average estimated cost of 65 AU$/MWh. Assuming the DOT will reduce those costs with 30%, the average electricity costs for wind energy will be circa 45 AU$/MWh, which is the lowest cost of all the sources.

Different types of mining consume different amounts of energy. Figure 34 (Australian Government, 2016) gives the average energy use for mining different types of minerals in Australia. The reason for the big differences between, for example, bauxite and gold, is that bauxite is not processed on site. Gold mines refine their products on location, which causes higher electricity needs. Also, the fuel prices differ per mining area. The price of grid electricity is mostly below AU$0.10/kWh. The electricity generated from pipeline gas ranges between AU$0.10/kWh and AU$0.30/kWh and the costs for off-grid diesel or gas generators are estimated between AU$0.15/kWh and AU$0.30/kWh.

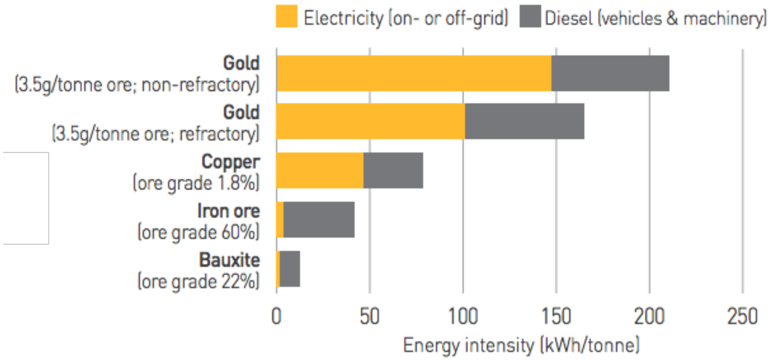


*Figure 34. Energy usage for different types of mining in Australia.*

To get an idea of the cost of one DOT wind turbine, an estimation can be made. The production costs of the DOT are estimated by its creators at around 70% of the costs of a conventional wind turbine (Diepenveen, 2017). For example, a land-based 1.5-MW wind turbine is estimated to cost around \$1.5 million (Fingersh, 2006). A comparable project with the DOT would be estimated at circa \$1.0 million, a decrease of circa \$0.5 million. In the case study of Tasmania, the average output power generated with one turbine is approximately 1 MW. Multiple turbines could be installed to obtain a total power output between 5 to 10 MW.

Comparing diesel generators with the DOT, the initial investment cost will be higher, because diesel generators are not that expensive. However, diesel generators have high maintenance costs each year. According to “Costs of Utility Distributed Generators” (Terrero, 2003), the annual maintenance costs are US\$5,000, based on an 1,800-kW generator, which operates 200 hours or less per year, which is approximately eight days. The maintenance cost of a generator operating up to 365 days will be much higher.

Using the DOT, maintenance costs will be cut. Where in conventional wind turbines the main parts are located in the nacelle, the DOT only has a pump. Parts that required high maintenance, like the gearbox and the generator are now located at ground level or are not present at all. Therefore, maintenance costs could be estimated at \$10,000 per year, if no parts have to be replaced.

However, the biggest improvement is the reduction of fuel costs. Where the input for the wind turbine is free, diesel generators consume fuel. Comparing the output of a 1 MW wind turbine, a Generac SD1000 is chosen. This is a diesel generator with an output of 1 MW (1000 kW). Table 25 shows an overview of the diesel consumption;

| Load (%) | Litre per hour | Cost per day (AU\$) | Cost per year (AU\$) |
|---|---|---|---|
| 25 | 92 | 2900 | 1.0 million |
| 50 | 160 | 5000 | 1.8 million |
| 75 | 233 | 7200 | 2.6 million |
| 100 | 295 | 9200 | 3.4 million |

*Table 25. Consummation and costs for a diesel generator per megawatt.*

If this generator runs at 100% load, the fuel consumption is 295 litres per hour. In Australia, the average price is AU\$1.30 per litre, which means that one day of continuous use costs more than AU\$9,000 per day. In one year the fuel costs alone will be AU\$3.4 million. Maintenance and transportation costs of the fuel are not included in this price. Given that other turbines, producing 1.5 MW, cost around \$1.0 million per turbine, the investment will give yield quickly.

## 6.7 Reduction of costs

An example of a mine that has partly switched to alternative energy, is the Diavik Diamond mine in the Northern Territories of Canada. This mine relied fully on diesel power generation. A large disadvantage is that the mine can only be reached over ice roads in winter, so 50 million litres of fuel have to transported and stored there. The costs per year are CA$70 million. The reliability on one fuel was questioned, and they were forced to explore other possibilities. In 2012 a wind farm was placed, with a capacity of 9.2 MW, which produces around 10% of the total mine electricity need, and thus saves approximately CA$5 million. The capital costs for the project were circa CA$31 million dollar, which will be earned back in circa eight years (Kirby, 2014).

However, the diesel generator cannot be turned off completely. As said, in Chile the average mine consumes circa 25 MW/hour per tonne of produced material (Jeswiet, 2015). Therefore, a 25 MW wind farm would have to be built. Using 1.5 MW wind turbines, seventeen turbines would have to be placed to get a maximum output of 25 MW. Unfortunately, the wind is not always at peak velocity, so the total output will usually be smaller than 25 MW. Therefore, the amount of wind turbines should be increased in order to maintain a more constant green power output, or a hybrid solution needs to be implemented.

It is hard to make a substantiated cost estimation, because almost all the parameters for the costs are dependent on location, mining type, wind speed and other variables. Also, the total costs of the DOT are not completely known. For a smaller 500 kW version, the price is estimated around €450,000. In the future, the turbines will be bigger and the costs will also be higher to produce the parts. But, comparing this with conventional wind turbines, the investment costs of the DOT will always be lower, with an estimation at 70% of the costs of conventional turbines (Diepenveen, 2017).

To calculate the average saving, the Levelized Costs of Electricity report can be used (Lazard, 2016). The report mentions low and high costs for different energy types in US$/MWh. Assuming the DOT electricity price is 70% of normal wind energy prices, an estimation of the cost reduction can be made.

| Type | Low ($/MWh) | High ($/MWh) |
|---|---|---|
| DOT | 23 | 44 |
| Wind | 32 | 62 |
| Diesel | 212 | 281 |

*Table 26. LCOE costs, estimated for 2016 (Lazard, 2016)*

Comparing the results from table 26, the conclusion is that per MWh the reduction could be significant. Comparing the highest estimation from the DOT with the lowest estimation for diesel generation, the cost will reduce with 168 $/MWh, a decrease of almost 80%.

Assuming the energy need of 25 MW/hour per tonne, using only diesel generators this will cost a minimal of $5300/hour per tonne of produced material. Assuming the DOT windfarm can produce an average 6 MW, the costs will be reduced to $4300/hour per tonne of produced material. In the best-case scenario, when the DOT produces all 25 MW, the costs could be reduced to $1100/hour per tonne of produced material.

## 6.8 Reduction of $CO_2$

Besides the decrease in costs of energy production, another important aspect is the decrease in $CO_2$-emissions. Where diesel generators cause a lot of pollution, wind turbines do not. In producing a wind turbine, $CO_2$ is emitted, but those emission are much lower compared to the emissions of a diesel generator.

Using the data from the Generac SD1000, previously mentioned, the maximum consummation per hour is 295 litres. According to Hanania (2014), a diesel generator uses 0.4 litres of fuel per generated kWh. The burning of the fuel creates the polluting gasses. Not only carbon dioxide ($CO_2$), but also nitrogen oxide ($NO_x$). Every litre of diesel contains 0.73 kilograms of pure carbon and 2.6 kilograms of $CO_2$. The emissions for the different loads can be seen in table 27;

| Load (%) | Litre per hour | kg Carbon per hour | kg $CO_2$ per hour |
|---|---|---|---|
| 25 | 92 | 65 | 240 |
| 50 | 160 | 115 | 415 |
| 75 | 233 | 170 | 605 |
| 100 | 295 | 215 | 770 |

*Table 27. Emissions of pure carbon and CO2 for the applied load of a 1MW diesel generator.*

This means that in a year the carbon emissions with a 100% load are 80,000 kg and the $CO_2$-emmission is circa 300,000 kg. The overall reduction of $CO_2$, when not using the Generac SD1000, will be 300,000 kg/year/MW. But, here it has to be mentioned that it is not likely turbines will take over the complete energy facility of a mine. Maybe in the future, but at this stage of the development there are too many uncertainties.

## 6.9 Direct internal hydraulic network

Using a hydraulic internal network instead of electricity could save energy and money. Where otherwise the wind is first converted to electricity and then back to a rotational motion, the hydraulic fluid can incite a hydraulic motor. Here, the pressure loss along the piping is important. The loss is mostly caused by friction along the pipe and due to heat transfer. Calculating the pressure drop along the length of the pipe, the following formulas are used;

Laminar Flow (Re < 2000):

$$f_D = \frac{64}{Re}$$

$$Re = \frac{\rho}{\mu} VD = \frac{VD}{\upsilon}$$

Turbulent Flow (Re > 2000):

$$\frac{1}{\sqrt{f}} = -2.00 \log \left(\frac{2.51}{Re * \sqrt{f_D}}\left(1 + \frac{1}{3.3} R_*\right)\right)$$

$$R_* = \frac{1}{\sqrt{8}} * \left(Re\sqrt{f_D}\right) * \left(\frac{\varepsilon}{D}\right)$$

| | | |
|---|---|---|
| Where | $Re$ | is the Reynolds number (-) |
| | $\rho$ | is the density (kg/m$^3$) |
| | $\mu$ | is dynamic viscosity (kg/m/s) |
| | $V$ | is flow speed (m/s) |
| | $D$ | is the diameter (m) |
| | $f_D$ | is the friction factor (-) |
| | $\varepsilon$ | is the surface roughness (m) |

To calculate the pressure loss, the SF Pressure Drop 8.0 software is used and a test system is developed. Screenshots of the software can be found in appendix A. Using the pressure generated by the DOT, fluid can be pumped, under pressure, through narrow tubes. This internal network can then be connected to a hydraulic motor or pump. Different pipes and bends cause pressure loss due to friction. To estimate the total pressure loss, figure 35 shows a simple network of hydraulic pressure with a hydraulic pump.

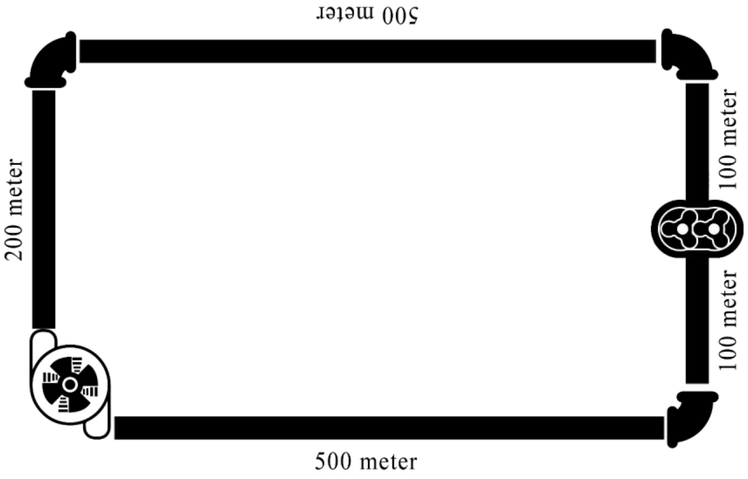


Figure 35. Schematic overview of the hydraulic internal loop.

Using the input power in MW and the pressure in bar, the flow speed can be calculated as follows;

$$\frac{Watt}{Pa} = \frac{\frac{kg * m^2}{s^3}}{\frac{kg}{m * s^2}} = \frac{kg * m^2}{s^3} * \frac{m * s^2}{kg} = \frac{m^3}{s}$$

Using the power output of 1 MW and a pressure of 200 bar, the flow will be 0.05 $m^3/s$ or 3000 lit/min. When oil is used as fluid, the density is 900 $kg/m^3$ and the kinematic viscosity is $70*10^{-6}$ $m^2/s$. For steel welded pipes, the roughness factor is 0.045 mm.

A 500 meter pipe with a 15 cm diameter will cause a pressure drop of 4.3 bar, which means the pipe has an efficiency of 97.8% for 500 meters. Then a 90-degrees circular bend with the same diameter and a radius of 30 centimetres causes a pressure drop of only 0.02 bar, which is almost negligible. A 100-meter pipe segment follows, which causes a 0.9 bar pressure drop. After that, a hydraulic motor is installed. From the initial 200 bar pressure, 194.8 bar is left. Assuming the overall efficiency of a pump/motor is 85%, which can be found in section 3.2. The pressure generated after the pump is 165.6 bar. Another 100 meter segment, a circular bend, a 500 meter pipe, a circular bend and a 200 meter pipe will connect the pipe to the pump driven by the DOT and a circular network is established. The remaining pressure at the end of the loop is 141.5 bar.

For the pump/motor, it is assumed that the efficiency is 85% with an inlet pressure of 194.8 bar remaining, before entering the motor. The remaining energy for the pump is:

$$\frac{3000\frac{lit}{min} * 194.8bar}{600} * 0.85\% \approx 830\ kW \approx 1100\ hp$$

When the loop is connected to the pump of the DOT, the 141.5 bar pressure will be upgraded again to the needed 200 bars.

# 7 Conclusion

This paper has answered the research question: What is the economic and environmental impact of using the DOT type wind turbine for the mining industry? It has shown that the Delft Offshore Turbine could be implemented to lower energy costs in the mining industry and increase its share towards a greener industry, and a greener world. The innovative system of the DOT makes it possible to not only lower the investment costs, but also reduces maintenance costs due to the removal of the gearbox and generator from the nacelle. By only using a hydraulic pump, the pressurized fluid could be used for generating electricity, but also for a direct internal hydraulic network. Where otherwise the pressure is converted to electricity and then back to a rotational movement, the pressure could directly drive a hydraulic motor, which then can create movement.

This paper has also explored possible test locations for the DOT. Logically, a windy location is mandatory. Also, enough mining projects have to be present in the area. A review suggested Australia as the most feasible location. It was also shown that in the future, other locations in the world could make use of the DOT.

Before the testing can begin, a system using wind energy combined with a more stable source has to be tested. At this stage, it is difficult to solely use power generated by the DOT. For this to be realised, a windfarm with a storage possibility would be needed in order to maintain a continuous supply of energy. The size of such a windfarm would be very large, and with the higher investment cost of wind turbines, it cannot be ensured that the investment is earned back within the lifetime of the mining operation.

However, the efficiency of the DOT is significantly higher than that of fossil fuel generators or electricity from the grid generated by, for example, coal. This efficiency would show profit in a windfarm of six to fifteen wind turbines, depending on the size and energy consummation of the mining operation. Even if a mine cannot rely fully on green wind power, an advantage is still achieved, as it is good for the costs and the environment.

In conclusion, it can be said that by using the DOT, the mining industry becomes greener. On a small scale, the costs can be reduced with up to 10%, but when upscaling the power output, a higher percentage can be realized. Replacing diesel generators by the DOT, thousands of litres of fuel will be saved each year. The saving of this fuel leads to reduction of $CO_2$ which can add up to 300,000 kilograms per MW per year.

Overall, the DOT cannot only be used in the offshore industry, but can also be useful in the mining industry. It can be used for different applications, which makes it a multifunctional device that makes it possible to cut the costs and make the mining industry a bit greener.

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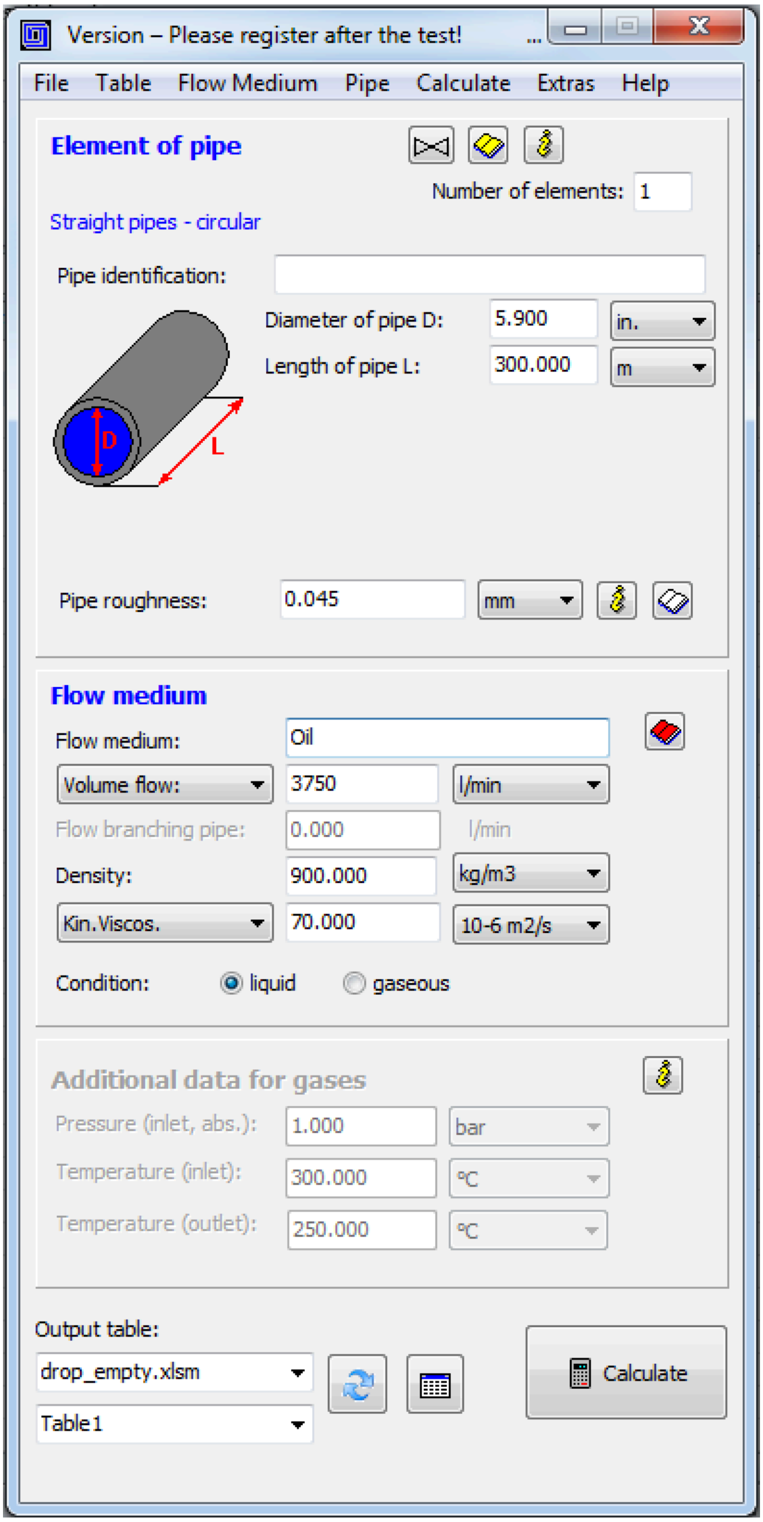
# 9 Appendices

## 9.1 Appendix A – Screenshot SF Pressure Drop Software



Version – Please register after the test!

**Element of pipe**

Number of elements: 1

Straight pipes - circular

Pipe identification:

Diameter of pipe D: 5.900 in.

Length of pipe L: 300.000 m

Pipe roughness: 0.045 mm

**Flow medium**

Flow medium: Oil

Volume flow: 3750 l/min

Flow branching pipe: 0.000 l/min

Density: 900.000 kg/m3

Kin.Viscos. 70.000 10-6 m2/s

Condition: ● liquid ○ gaseous

**Additional data for gases**

Pressure (inlet, abs.): 1.000 bar

Temperature (inlet): 300.000 °C

Temperature (outlet): 250.000 °C

Output table: drop_empty.xlsm

Table1

*Figure 36. Screenshot of the Pressure Drop SF software.*