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ANALYSIS OF DUCTED (OR DIFFUSER-AUGMENTED) WIND TURBINE

BY ECATERINA JERNOVAIA

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Title	**Analysis of the ducted (or diffuser augmented) wind turbines**

Student **Ecaterina Jernovaia**
+41 76 483 78 97
ecaterina.jernovaia@stud.hslu.ch

Bachelor's degree program **Bachelor in Energy Systems Engineering**

Semester **fall semester 20**

Lecturer **Dr. Deniz Sabri**
+41 41 349 32 54
sabri.deniz@hslu.ch

External examiner **Dr. Joel Schlienger**
joel.schlienger@ch.abb.com

Abstract

With the introduction of the Energy Strategy 2050 and its goal of increasing the quantum of renewable energy production, wind energy is seen to be indispensable to help integrate these technologies. Wind Energy is fast becoming a significant source of energy throughout the world. This ever-expanding field will potentially reach the limit of availability and practicality with the wind farm sites and size of the turbine itself. Therefore, it is necessary to develop innovative wind capturing devices that can produce energy in the locations where large conventional horizontal axis wind turbines (HAWTs) are too impractical to install and operate. A diffuser-augmented wind turbine (DAWT) is one such innovation. DAWTs increase the power output of the rotor by increasing the wind speed into the rotor using a duct. Currently, developing these turbines is an involved process, using time consuming Computational Fluid Dynamics codes. A simple and quick design tool is necessary for designers to develop efficient energy capturing devices. This work lays out the theory for a quick analysis tool for DAWTs using the basic fluid dynamic equations method, in combination with Excel. It permits quick analysis of optimum geometry giving designers a general idea of the area ratios, length and opening angles of nozzle and diffuser parts.

Lucerne, 04 January 2021

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Abbreviations and acronyms

CFD	Computational Fluid Dynamics
DAWT	Diffuser Augmented Wind Turbine
EU	European Union
HAWT	Horizontal Axis Wind Turbine
HSLU	Hochschule Luzern
RE	Renewable Energy
rpm	Revolutions per minute
UK	United Kingdom
US	United States
VAWT	Vertical Axis Wind Turbine
WWEA	World Wind Energy Association

1 Introduction

With the severe energy crisis confronting the modern world, the production and utilization of energy have become a vital issue, and the conservation of energy has acquired prime importance. Energy production and consumption are directly related to everyday life in much of human society, and issues of energy research are extremely important and highly sensitive. With the growing awareness of the global warming problem, humans tend to rely more on renewable energy (RE) resources.

Wind power capacity has increased dramatically in the U.S and Europe, but compared to European solar and wind power generation, Switzerland ranks near the bottom. Switzerland produces only 14 kilowatt hours of wind power per year per capita. Geographical disadvantages and incentive structure make the installation of large wind turbines in Switzerland economically challenging. Therefore, some Swiss companies are working on the development of smaller scale wind turbines for residential use, installed at communities or rural areas (decentralized energy) as well as on hybrid systems i.e., the combination of solar and wind energy installed for example on the roofs (e.g., Windrail or "Dachziegel"). Among new or unconventional types of small-scale wind turbines, the ducted or diffuser-augmented (DAWT) model is promising. The ducted (or diffuser-augmented) wind turbine has the ability to accelerate the airflow through a converging duct intake, thereby increasing the power extracted from airflow significantly; however, there is also some controversy about the advantages of the DAWT against the conventional wind turbines. One of the important challenges is to design a DAWT, which can capture wind from different directions.

1.1 Project aim and objectives

This study aims to analyze the ducted or diffuser-augmented wind turbines as a sustainable source of power for small scale applications and try to "optimize" the converging-diverging duct geometry for maximum power output and for capturing as much airflow as possible at the intake, considering the relevant geometrical and operational parameters. The main research objectives are to define the optimum geometry of the diffuser-augmented wind turbine, compare it with the conventional wind turbine in terms of efficiency, power, cost, and reliability and propose solutions for capturing maximum wind flow.

The Methodology is represented in Chapter 3, providing research instruments and tools used to conduct the research and answer the research question. This chapter describes the approaches to the literature review, identifying and analyzing key geometry parameters, combining the parameters to maximize the performance coefficient and consequently the power output of the diffuser-augmented wind turbine.

Chapter 4 deals with research results consisting of three key elements, viz., flow analysis, geometry optimization, comparison of the results with previous studies, and comparison of the conventional wind turbine and diffuser-augmented wind turbine in terms of performance and economics. The recommendations based on the results of the study and outlook are outlined in Chapter 7.

2 Literature review

This chapter provides, a wind turbine overview, it's work principle and main parameters, applications of wind turbine, current capacity and trends of wind power in Switzerland, Europe, and worldwide.

2.1 Wind turbine overview

A wind turbine transforms the kinetic energy in the wind to mechanical energy in a shaft and finally into electrical energy in a generator. The maximum available energy, P_{max}, is thus obtained if theoretically the wind speed could be reduced to zero and can be calculated using Formula 1.

$$P = 1/2\,\dot{m}V_0^3 = 1/2\,\rho A V_0^3 \tag{1}$$

With:

P = power [W]

$\dot{m}$ = mass flow [kg/s]

V_0 = wind speed [m/s]

ρ = density of the air [kg/m^3]

A = area where the wind speed has been reduced [m^2]

The equation for the maximum available power is very important since it tells us that power increases with the cube of the wind speed and only linearly with density and area. The available wind speed at a given site is therefore often first measured over a period of time before a project is initiated.

In practice one cannot reduce the wind speed to zero, so a power coefficient C_p is defined as the ratio between the actual power obtained and the maximum available power as given by the above equation. A theoretical maximum for C_p exists, denoted by the Betz limit, $C_{p\,max} = 16/27 = 0.593$. Modern wind turbines operate close to this limit, with C_p up to 0.5 and are therefore optimized. Statistics have been given on many different turbines sited in Denmark and as rule of thumb they produce approximately $1000\ kWh/m^2/year$. However, the production is very site dependent and the rule of thumb can only be used as a crude estimation and only for a site in Denmark.

Sailors discovered very early on that it is more efficient to use the lift force than simple drag as the main source of propulsion. Lift and drag are the components of the force perpendicular and parallel to the direction of the relative wind respectively. It is easy to show theoretically that it is much more efficient to use lift rather than drag when extracting power from the wind. All modern wind turbines therefore consist of a number of rotating blades looking like propeller blades. If the blades are connected to a vertical shaft, the turbine is called a vertical-axis machine, VAWT, and if the shaft is horizontal, the turbine is called a horizontal-axis wind turbine, HAWT. For commercial wind turbines the mainstream mostly consists of HAWTs; the following text therefore focuses on this type of machine. A HAWT as sketched in Figure 1 is described in terms of the rotor diameter, the number of blades, the tower height, the rated power and the control strategy.

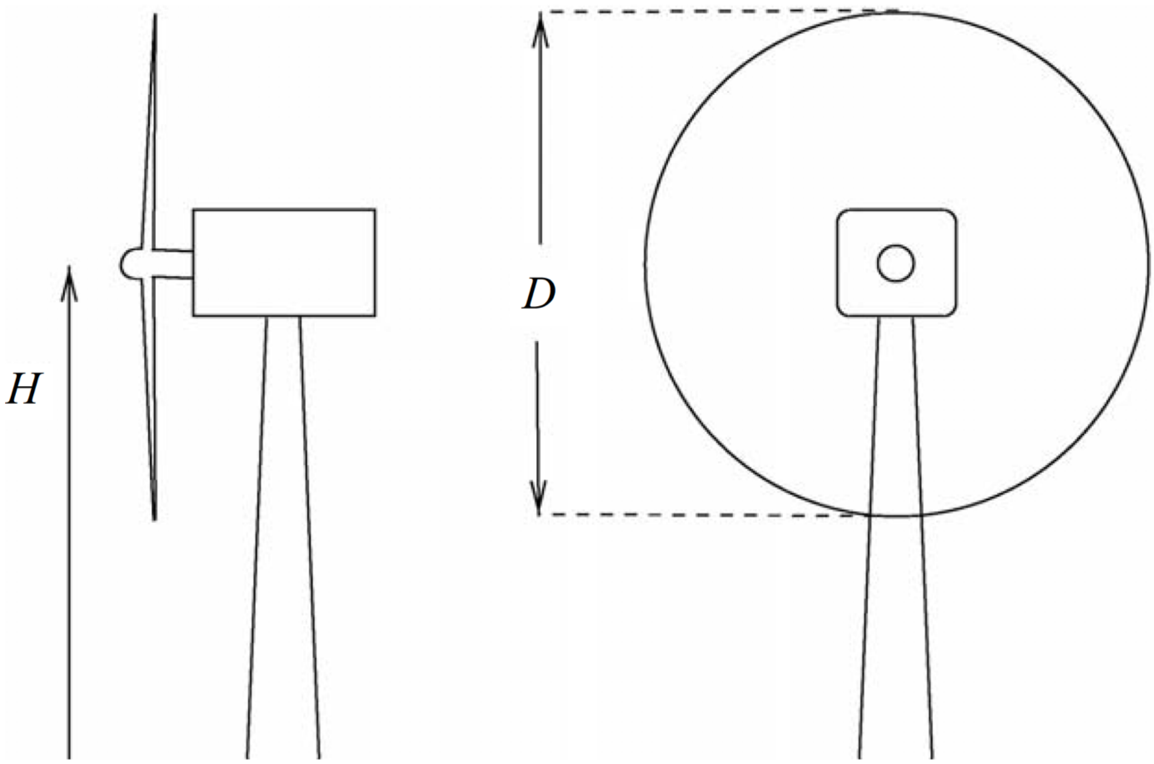

Figure 1: Horizontal axis wind turbine (HAWT) from Aerodynamics of wind turbines by Hansen

The tower height is important since wind speed increases with height above the ground and the rotor diameter is important since this gives the area A in the formula for the available power. The ratio between the rotor diameter D and the hub height H is often approximately one. The rated power is the maximum power allowed for the installed generator and the control system must ensure that this power is not exceeded in high winds. The number of blades is usually two or three. Two-bladed wind turbines are cheaper since they have one blade fewer, but they rotate faster and appear more flickering to the eyes, whereas three-bladed wind turbines seem calmer and therefore less disturbing in a landscape. The aerodynamic efficiency is lower on a two-bladed than on a three-bladed wind turbine. A two-bladed wind turbine is often, but not always, a downwind machine; in other words, the rotor is downwind of the tower. Furthermore, the connection to the shaft is flexible, the rotor being mounted on the shaft through a hinge. This is called a teeter mechanism and the effect is that no bending moments are transferred from the rotor to the mechanical shaft. Such a construction is more flexible than the stiff three-bladed rotor and some components can be built lighter and smaller, which thus reduces the price of the wind turbine. The stability of the more flexible rotor must, however, be ensured. Downwind turbines are noisier than upstream turbines, since the once-per-revolution tower passage of each blade is heard as a low frequency noise.

The rotational speed of a wind turbine rotor is approximately 20 to 50 rpm and the rotational speed of most generator shafts is approximately 1000 to 3000 rpm. Therefore, a gearbox must be placed between the low-speed rotor shaft and the high-speed generator shaft. The layout of a typical wind turbine can be seen in Figure 2, showing a Siemens wind turbine designed for offshore use. The main shaft has two bearings to facilitate a possible replacement of the gearbox.

This layout is by no means the only option; for example, some turbines are equipped with multipole generators, which rotate so slowly that no gearbox is needed. Ideally a wind turbine rotor should always be perpendicular to the wind. On most wind turbines a wind vane is therefore mounted somewhere on the turbine to measure the direction of the wind. This signal is coupled with a yaw motor, which continuously turns the nacelle into the wind.

The rotor is the wind turbine component that has undergone the greatest development in recent years. The airfoils used on the first modern wind turbine blades were developed for aircraft and were not optimized for the much higher angles of attack frequently employed by a wind turbine blade. Even though old airfoils, for instance NACA63-4XX, have been used in the light of experience gained from the first blades, blade manufacturers have now started to use airfoils specifically optimized for wind turbines. Different materials have been tried in the construction of the blades, which must be sufficiently strong and stiff, have a high fatigue endurance limit, and be as cheap as possible. Today most blades are built of glass fiber reinforced plastic, but other materials such as laminated wood are also used. (Hansen et. al, 2015)

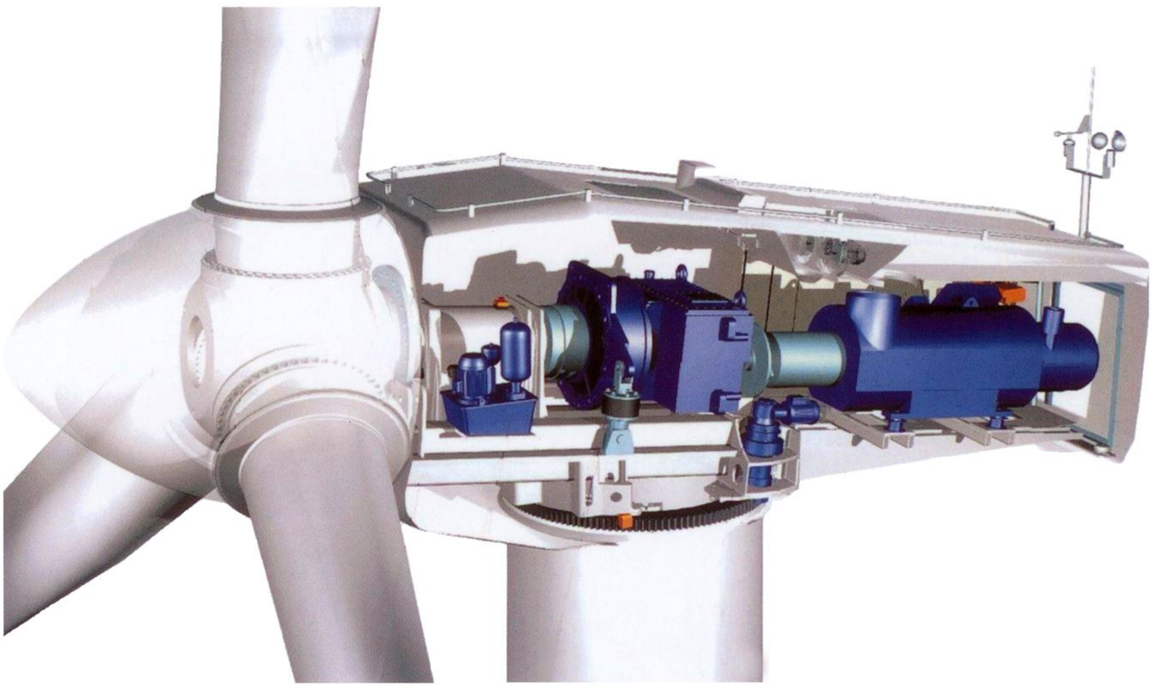

Figure 2: Layout of a modern wind tower from: https://www.speedgoat.com/userstories/speedgoat-user-stories/wind-technologies

2.2 Applications of wind turbine

The range of wind power usage is scarce. One of the most important usages is electricity (Hubbard & Shepherd, 1990). Wind turbine generators, range in capacity from a few kilowatts to several megawatts, for producing electricity both singly and in wind power stations that encompass hundreds of machines. According to researchers, there are many installations in uninhabited areas far from established residences, with no apparent environmental impacts in terms of noise. Researchers do point out, however, situations in which radiated noise can be heard by the residents of adjacent neighborhoods, particularly those who live in neighborhoods with low ambient noise levels (H. Hubbard & Shepherd, 1990).

Wind power is used not only in developed countries, but worldwide. Specific studies presented a detailed study of a Manchegan windmill, while considering the technological conditions of the original Manchegan windmills. In addition, a wind evaluation of the region was carried out, the power and momentum of the windmills were calculated, and the results obtained were discussed, along with a comparison with the type of Southern Spanish windmill. These windmills were important for wheat milling and were an important factor in the socio-economic development of rural Spain for centuries (Rojas-Sola & Manuel, 2005).

Al-Mohamed et Al (2003) evaluated both wind energy potential and the electricity that could be generated by the wind in Syria. An appropriate computer program was especially designed to perform the required calculations, using the available meteorological data provided by the Syrian Atlas. The program is capable of processing the wind data for any specific area that conforms to the requirements in fields of research and application. Calculations in the study show that a significant energy potential is available for direct exploitation and that approximately twice the current electricity consumption in Syria can be generated through wind resources (Al-Mohamed et al., 2003)

The potential usage of wind power at Kudat and Labuan for small-scale energy demand was given in "*Assessment of wind energy potentiality at Kudat and Labuan, Malaysia using Weibull distribution function*" by Islam et al. According to the authors, the acquisition of detailed knowledge about wind characteristics at a site is a crucial step in planning and estimating performance for a wind energy project. Accordingly, the researchers concluded that sites at Kudat and Labuan were unsuitable for large scale wind energy generation. However, they did confirm that small scale wind energy could be generated at a turbine height of 100 meters. In light of their findings, James et al. (2010) reported that the potential impact of UK's latest policy instrument, the 2010 micro-generation tariffs, is considered applicable to both micro-wind and photovoltaics.

As the researchers observed, building-mounted micro-wind turbines and photovoltaics have the potential to provide widely applicable, carbon-free electricity generation at the building level. As photovoltaic systems are well understood, it is easy to predict performance using software tools or widely accepted yield estimates. Micro-wind research, however, is far more complex and poorly understood.

Unlike electricity derived from fossil fuel and nuclear power plants, wind power consumes no fuel and unlike fossil fuel power plants, causes no air pollution in operation. There are reports of bird and bat mortality at wind turbines, as there are around other artificial structures. The scale of the ecological impact may or may not be significant, depending on specific circumstances.

Wind energy keeps more of your energy dollars local! When you pay for electricity, you are paying for many things — the cost of building and operating the power plant, the cost of maintaining the electrical grid, and so on. When electricity is produced using fossil or nuclear fuels, the single biggest cost built into your electricity bill is that of the fuel needed to run the power plant. For most of us, that fuel comes from another state, or even another country.

Wind energy is different. The wind is free and there is no need to purchase fuel. At the same time, wind parks create more local economic development than any other type of electrical generation. (Qaddoura et al. 2013)

2.3 Wind energy potential

This section provides information regarding wind power current situation as well as its potential in Switzerland, Europe, and worldwide.

2.3.1 Wind energy in Switzerland

The first wind energy facility in Switzerland became operational in 1986 near Soolhof (Langenbruck, Canton of Basel-Landschaft), with an output of 28 kilowatts. Today, there are 40 large wind energy facilities operating in Switzerland, which produce a total of 140 gigawatt hours of electricity. The largest wind park is on Mont Crosin in the Bernese Jura near St Imier and comprises 16 wind turbines with a total output of 37.2 megawatts. Other large facilities are in the Rhône Valley (Canton of Valais), Entlebuch (Canton of Lucerne) and on the Gütsch (above Andermatt, Canton of Uri).

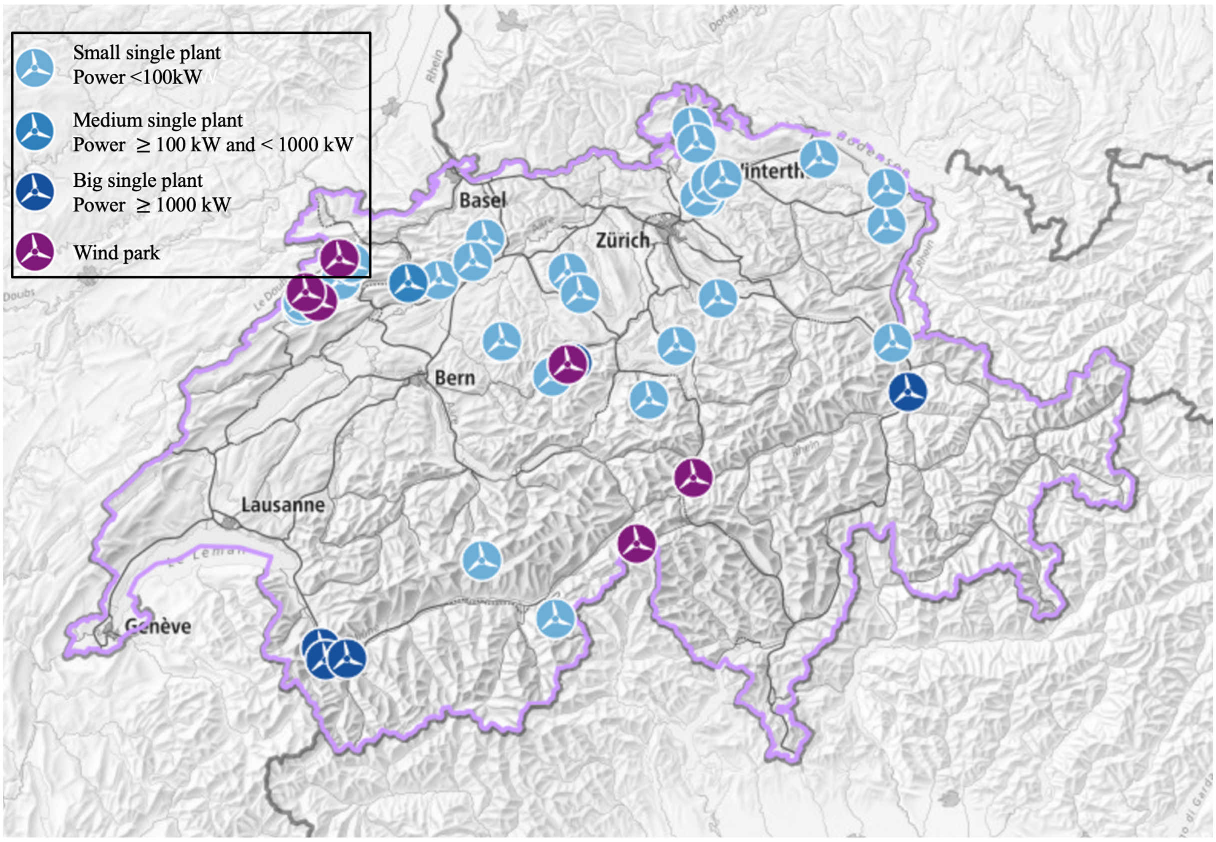

Figure 3: Wind energy plants in Switzerland from: https://www.uvekgis.admin.ch/BFE/storymaps/EE_WEA/index.php?lang=en

Figure 3 shows the location of small and large-scale wind energy plants in Switzerland, together with their respective capacities and the quantum of electricity produced in the past few years. All data are based on information provided by the power plant operators, intended as information for the general public.

In 2020, a total of 37 wind power plants produced around 140 gigawatt hours (GWh) of electricity in Switzerland. The largest wind park is on Mont Crosin in the Bernese Jura near St Imier, comprising 16 wind turbines with a total output of 37.2 megawatts. Other large facilities are in operation in Rhonetal (canton of Valais), near Entlebuch (canton of Lucerne) and on the Gütsch (above Andermatt, canton of Uri).

There is still a substantial potential for wind energy in Switzerland. The goal is to increase the annual production of electricity from wind energy plants to around 600 GWh by 2020 and 4000 GWh by 2050. Suitable locations for wind parks exist in the Jura range, in the Alps and the western region of the central plateau.

In Switzerland, wind energy plants produce two-thirds of their electricity during the winter, i.e. precisely when we need more energy for heating and electricity for lighting, making wind energy an ideal supplement to hydropower and solar power, which have their peak production during the summer.

2.3.2 Wind energy in Europe

With an average of 12.6 GW per year (Figure 4), volumes of new deployment of wind energy capacity look set to remain fairly strong through to 2020, according to WindEurope's Central Scenario. Year 2017 was expected to mark a record high in annual installations, with 50 GW to be installed during 2017-2020, bringing the cumulative installed capacity of the European Union (EU) to 204 GW. This 50 GW of additional capacity would represent over half of all new renewable capacity in the EU over the 4-year period, well above solar PV, bioenergy and hydropower.

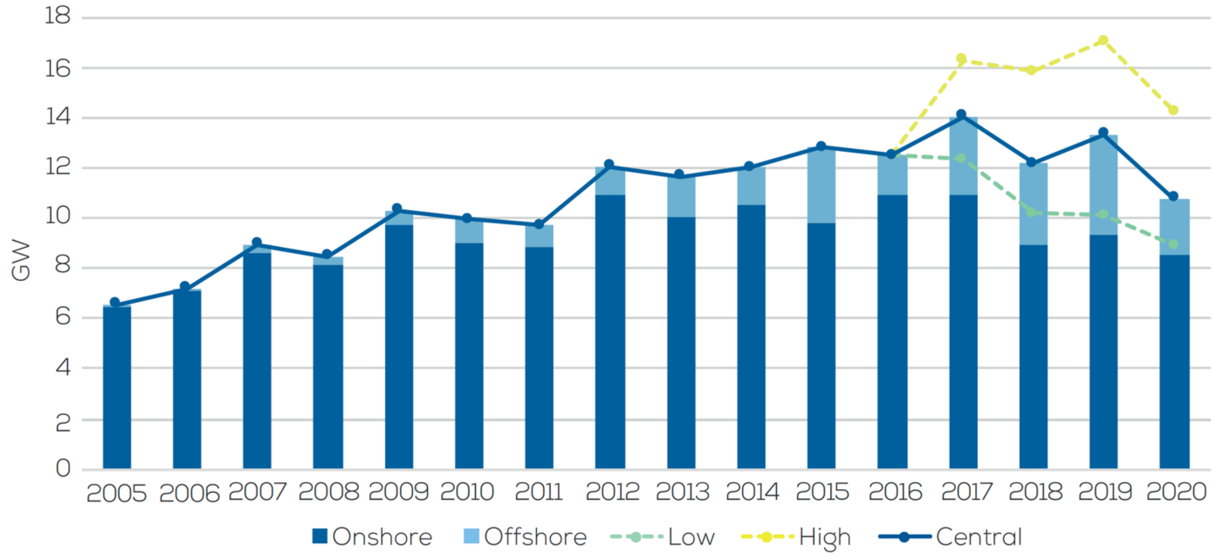

Figure 4: Wind energy market outlook to 2020 in Europe from WindEurope

With over 200 GW of installed capacity, wind energy could meet 16.5% of Europe's electricity needs by 2020, surpassing hydro power and becoming the largest source of renewable electricity. Denmark is expected to meet over half of its demand through wind energy and Germany, almost 30%. Ireland, Portugal, Spain and the UK will follow with 29, 27, 24 and 21% respectively. New installations will remain relatively strong till end-2020, but policy uncertainty and lack of ambition for the post-2020 climate and energy framework could have a significant negative impact on the sector. Only a handful of Member

States have provided visibility and regulatory certainty. With only 5 of the EU-28 announcing auction plans, there is a lack of certainty on revenue stability for investors (Nghiem et al. 2017).

Market concentration will remain high, with Germany, UK, France, Spain and the Netherlands installing most of the capacity. Germany alone will represent a third of all the installed capacity, with a total of 16.5 GW, followed by UK, with two thirds of its new installations offshore. France will be third, with potential installations of up to 6.5 GW.

The onshore market will remain stable with a slight decrease towards the end of the 4-year period, mainly due to lower activity planned in Germany. However, we expect Spain to experience radical growth after several years of inactivity; following the recent tenders, the industry is gearing up to install 4.1 GW of capacity.

The offshore market will grow at a higher pace than the onshore market. With average new installations of 3.1GW/year, offshore wind will represent about one quarter of the total new installations (compared to a 15% share during 2013-2016). The offshore market will concentrate mainly in the UK with 5.2 GW, representing 42% new grid-connected capacity. Four others will see offshore installations: Germany (3.5 GW), Belgium (1.5 GW), the Netherlands (1.4 GW) and Denmark (1.0GW). In 2019, offshore annual installations will reach over 4 GW investors (Nghiem et al. 2017).

2.3.3 Wind energy worldwide

The overall capacity of wind turbines installed worldwide by the end of 2019 reached 650,8 Gigawatt, according to World Wind Energy Association (WWEA), with 59'667 Megawatt added in 2019, substantially more than the previous year, accounting for 50'252 Megawatt. 2019 was the second strongest wind year in terms of market size, with a growth rate of 10,1 %, higher than the 9,3 % of the previous year, but lower than 2016 and 2017. All wind turbines installed by end of 2019 can cover more than 6% of the global electricity demand. Total installed capacity of wind power worldwide is depicted in Figure 5.

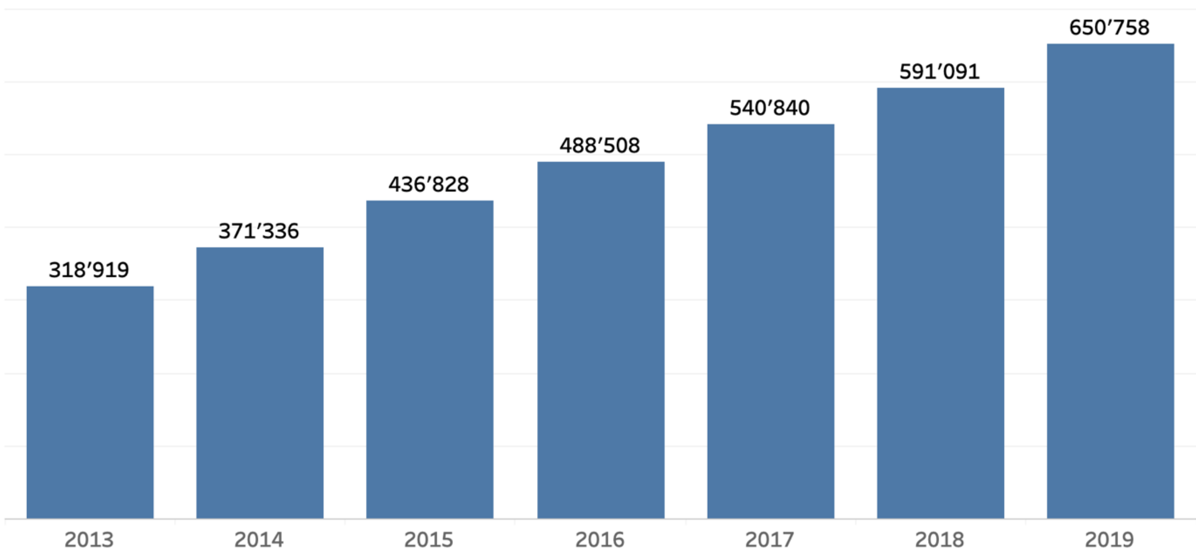

Figure 5: Total installed capacity of wind energy worldwide [MW] from Library by Jean-Dainel Pitteloud

China and the US had strong years, with 27,5 Gigawatt and 9,1 Gigawatt of new installations respectively, representing the biggest market volume in the last five years in both the countries. In particular, most of the European markets suffered from insufficient policies and faced a strong decline, led by the poor performance of the former world leader Germany, which only added 2 Gigawatt, down from 6,2 Gigawatt in 2017.

The current corona virus crisis has had a global impact on the market development in 2020, and consequently, the wind industry worldwide has experienced a general slowdown. Disrupted international supply chains and national lockdown regulations are both hampering the wind sector, like most other industries. Stefan Gsänger, WWEA Secretary General, says: "Many governments have started to prepare plans and stimulus programmes to restore their economy after the corona crisis. WWEA's advice to all governments: put investments in renewable energy, including wind power, at the center of your economic strategies. Not only will this help overcome the economic devastation caused by the corona crisis, it will also address the world's second challenge, the climate crisis. The transition to a renewable energy economy will ultimately not cause major financial burdens, but will bring manifold social, economic and ecological benefits." (n.a. 2020)

2.4 Overview of diffuser augmented wind turbine

Wind power generation is proportional to the wind speed cubed. Therefore, a large increase in output is affected if it is possible to create even a slight increase in the velocity of the wind approaching a wind turbine. If we can increase the wind speed by utilizing the fluid dynamic nature around a structure or topography, that is, if we can concentrate the wind energy locally, the power output of a wind turbine can be increased substantially. Although there have been several studies of collecting wind energy for wind turbines reported so far, it has not been an attractive research subject conventionally. Unique research was carried out by Gilbert et al. (1980) intensively in the past concerning of a diffuser-augmented wind turbine. In these studies, there was a focus on concentrating wind energy in a diffuser with a large open angle; a boundary layer controlled with several flow slots was employed to realize a flow that goes along the inner surface of the diffuser. Thus, the method of boundary layer control prevents pressure loss by flow separation and increases the mass flow inside the diffuser. Based on this idea, a group in New Zealand developed the Vortec 7 diffuser-augmented wind turbine. They used a multi-slotted diffuser to prevent separation within the diffuser. Bet and Grassmann developed a shrouded wind turbine with a wing-profiled ring structure, their DAWT showing an increase in power output by the wing system by a factor of 2.0, compared to the bare wind turbine. Although several other ideas have been reported so far, most do not appear to be reaching the commercialization stage.

The performance enhancement of a Diffuser-augmented Wind Turbine depends on several factors including the diffuser shape and geometries, blade airfoils and wind condition at the mounting site. Geometric features are the main parameters controlling the aerodynamic performance of this wind-energy device (Fig. 6). The geometry of DAWT is denoted by dimensions of diameter of inlet diffuser, which is related by rotor diameter (D), diffuser length (L), diffuser angle (α) and brim height (flange height) (H), as shown in Figure 6. Each of these geometrical parameters has a direct or indirect effect on DAWT performance.

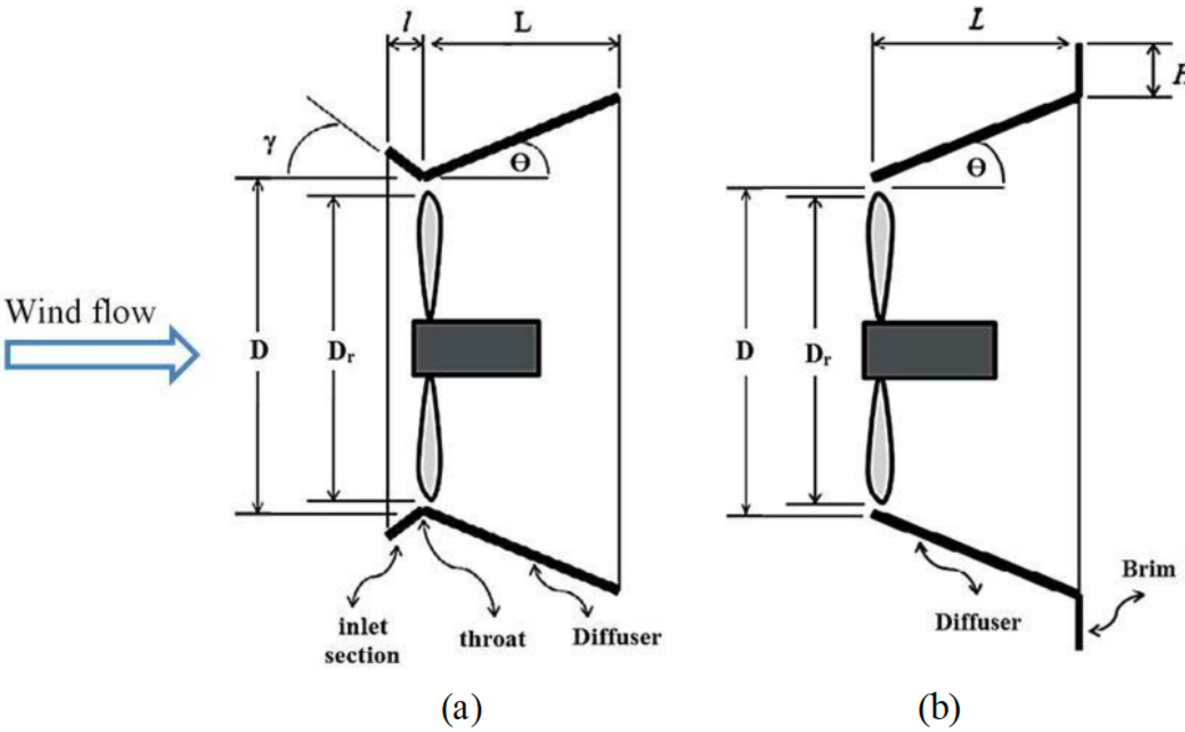

Figure 6: Typical shroud designs for wind turbine: a) nozzle-diffuser b) diffuser-brim shroud from Fluid dynamics of diffuser-augmented wind turbines by Gilbert at. al

One of the application examples is ‘Windrail’ concept that is supposed to combine diffuser augmented wind turbine and PV panels as demonstrated below (Fig. 7):

Figure 7: Concept of the building with 'WindRail' diffuser augmented wind turbines in combination with PV panels on the roof form http://www.anerdgy.com

3 Methodology

This chapter explains in detail the methodology being used to achieve the aims and objectives of the project, and the methods used to approach each stage of the project development. The structure of the report, with the corresponding methods, is presented in the diagram (Fig.8) below. A more detailed description of all methods is furnished in the following sub-chapters.

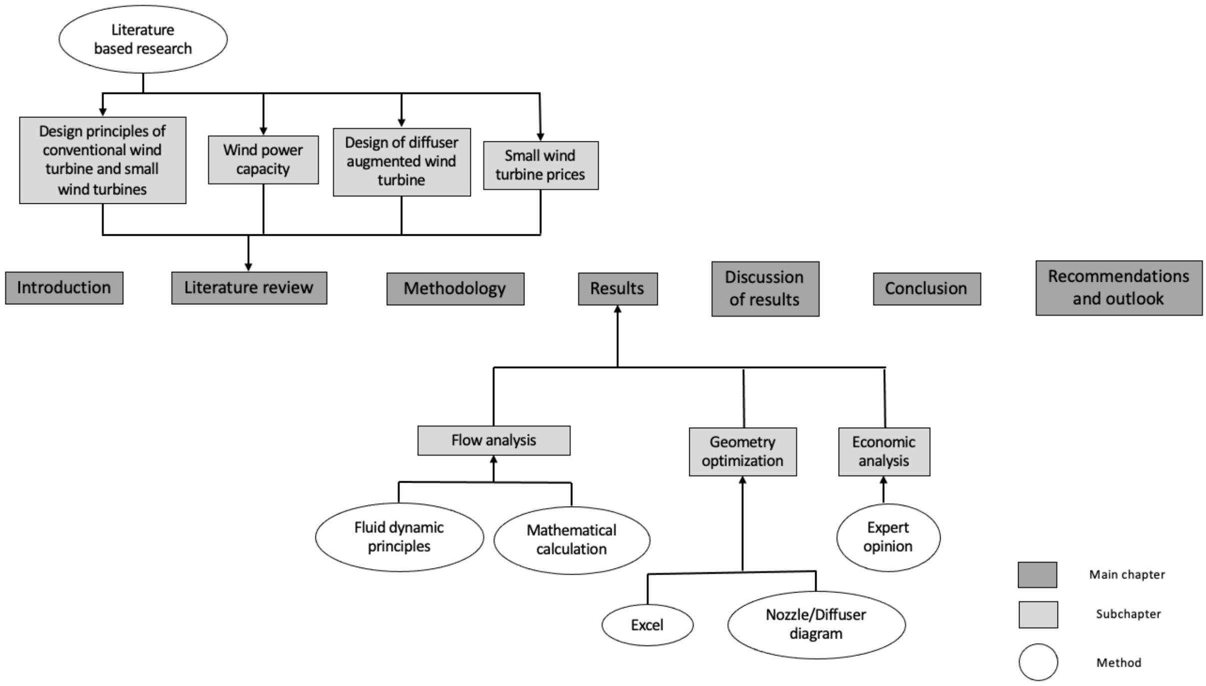

Figure 8: Overview of the report's structure and methods

3.1 Literature review

For optimizing the geometry of the diffuser-augmented wind turbine, the first step is to gather enough information about the working principle of the conventional wind turbine, application of wind power and its capacity and potential related to the strategy of shifting from fossil fuels to renewable energy sources. The next stage is to understand the technical aspect of diffuser-augmented wind turbine, its main advantages, challenges and possible solutions, and the basic geometrical parameters that influence wind turbine performance. The main sources are studies, reports, academic scripts and textbooks found in the library and Internet.

3.2 Flow analysis

Flow analysis was performed to define important geometrical parameters of the nozzle and diffuser and manipulate them to obtain the maximum performance coefficient.

Continuity equation, Bernoulli equation, and some assumptions permitted the derivation of the performance coefficient of the diffuser-augmented wind turbine ($c_{p,DAWT}$) as a function of the area ratios of nozzle and diffuser. An important assumption was not to consider the rotor in the derivation of the mathematical equation of performance coefficient. The next step was the implementation of partial derivatives in order to maximize the function. However, the analytical approach with fluid dynamic assumptions does not yield fruit. Therefore, literature review was applied again to set optimum nozzle and diffuser area ratios as a starting point to get maximum performance coefficient of the diffuser-augmented wind turbines. For further adjustments and improvements of nozzle and diffuser, ‘nozzle’ and ‘diffuser’ diagrams were used.

3.3 Excel simulation in combination with ‘diffuser’ diagram

Geometrical parameters identified in previous stage of the research and their optimum values found in the literature review, were manipulated in Excel based on the ‘nozzle’ (Fig.9) and ‘diffuser’ (Fig. 10) diagrams in order to maximize the performance coefficient and concequently, the power output of diffuser augmented wind turbine.

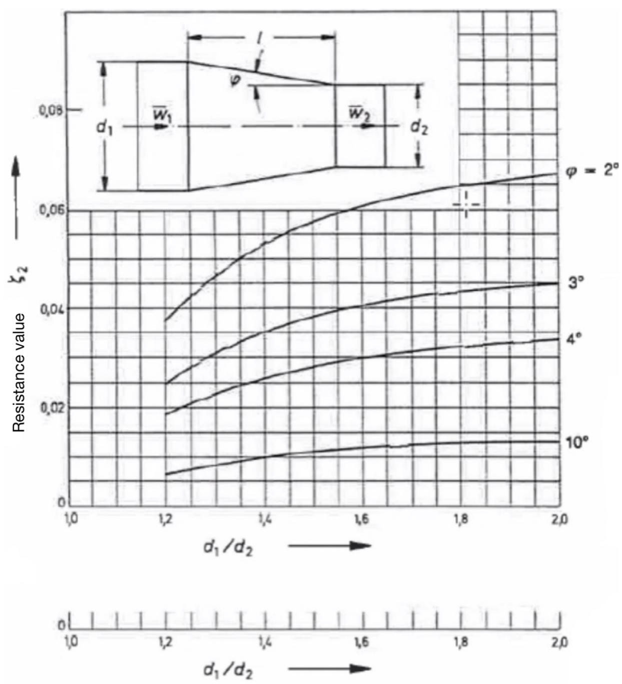

Figure 10: 'Nozzle' diagram be Kleine et al.

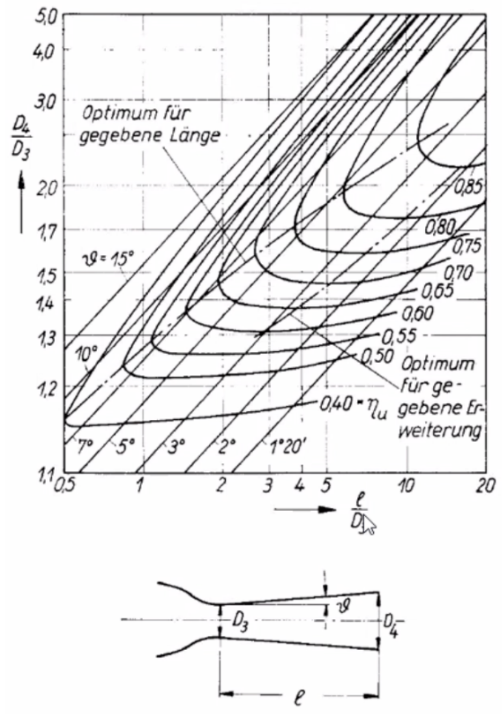

Figure 9: 'Diffuser' diagram from dDiffuser Design Technology by Japikse et al.

3.4 Expert opinion

This method was used in order to obtain insights on the diffuser-augmented wind turbine prices, in comparison with those of the traditional wind turbine. The expert is Dr. Alessabro Bianchini, a professor and researcher from Italian university in Firenze, active in the research area of wind turbines.

4 Results

In this section, the results have been organized into five sub-sections. The first section summarizes the equation derivation for the subsequent flow analysis and geometry optimization, while the second focuses on the geometry optimization and the third on the comparison of conventional and diffuser-augmented wind turbine in terms of performance and power output. The fourth section compares the results of this study with previous studies and the fifth details the economic analysis of diffuser-augmented wind turbine.

4.1 Flow analysis

The one-dimensional analysis of a conventional bare turbine is based on the assumption of its representation as an actuator disc. The disc is considered ideal, as it is frictionless and without any rotational velocity component in the wake. The entire process is assumed to occur at a small Mach number and the air density is thus constant. The flow is also assumed to be steady, incompressible and friction-less and there are no external forces acting on the fluid up- or down-stream of the turbine. Figure 11depicts the diffuser-augmented wind turbine geometry with all important notations considered in the following formulas. Formulas are derived with 1=inlet; 2, 3=rotor; 4=outlet.

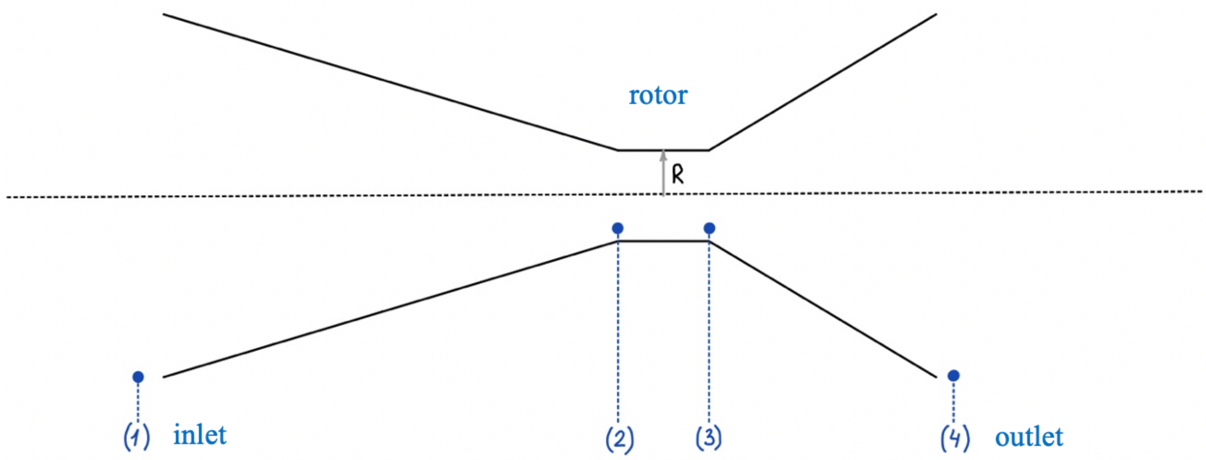

Figure 11: Schematic of Diffuser Augmented Wind Turbine (DAWT)

Continuity equation of the nozzle-diffuser system of DAWT (considering that the fluid is incompressible ⇒ $\rho = const$):

$$A_1 v_1 = A_2 v_2 = A_3 v_3 = A_4 v_4 \tag{2}$$

With:

A = Area [m^2]

v = Velocity [m/s]

Bernoulli equation (considering that there are no losses):

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2 \tag{3}$$

$$p_3 + \frac{1}{2}\rho v_3^2 = p_4 + \frac{1}{2}\rho v_4^2 \tag{4}$$

With:

p = pressure [Pa]

ρ = air density [kg/m^3]

Assuming that $p_1 = p_4 = p_{atm} = 0$ (In real case $p_4 < p_{atm}$)

$$\Rightarrow \; p_2 = \frac{1}{2}\rho(v_1^2 - v_2^2)$$

$$p_3 = \frac{1}{2}\rho(v_4^2 - v_3^2)$$

$$p_2 - p_3 = \Delta p = \frac{1}{2}\rho(v_1^2 - v_2^2 + v_3^2 - v_4^2) \tag{5}$$

With p_{atm} = atmospheric pressure in Pa.

From (2): $v_2 = v_3$ because $A_2 = A_3$

$$\Rightarrow p_2 - p_3 = \frac{1}{2}\rho(v_1^2 - v_4^2) \tag{6}$$

From (2): $v_4 = v_3\frac{A_3}{A_4}$ and $v_1 = v_2\frac{A_2}{A_1}$

Plug it in equation (5):

$$p_2 - p_3 = \frac{1}{2}\rho\left(v_2^2\left(\frac{A_2}{A_1}\right)^2 - v_3^2\left(\frac{A_3}{A_4}\right)^2\right) \tag{7}$$

Since $v_2 = v_3 = v_R$ because $A_2 = A_3$:

$$p_2 - p_3 = \frac{1}{2}\rho v_R^2\left(\left(\frac{A_2}{A_1}\right)^2 - \left(\frac{A_3}{A_4}\right)^2\right) = \Delta p_R \tag{8}$$

With ‘R’ standing for rotor.

Equation (8) displays the ideal pressure drop across the turbine based on the actuator disc instead of the wind turbine rotor.

The maximum power coefficient of diffuser augmented wind turbine:

$$c_{p,DAWT} = \frac{\Delta p_R \cdot A_R \cdot v_R}{\rho \cdot \frac{1}{2} \cdot A_R \cdot v_0^3} \tag{9}$$

With:

$A_2 = A_3 = A_R$

$v_2 = v_3 = v_R$

v_0= free stream velocity at the inlet ($v_0 \approx v_1$) [m/s]

$c_{p,DAWT}$ = performance coefficient of diffuser augmenter wind turbine

$$\Rightarrow c_{p,DAWT} = \frac{\Delta p_R \cdot A_R \cdot v_R}{\rho \cdot \frac{1}{2} \cdot A_R \cdot v_0^3} = \frac{\frac{1}{2}\rho v_R^2 \left[\left(\frac{A_2}{A_1}\right)^2 - \left(\frac{A_3}{A_4}\right)^2\right] \cdot A_R \cdot v_R}{\rho \frac{1}{2} A_R v_0^3} = \left[\left(\frac{A_2}{A_1}\right)^2 - \left(\frac{A_3}{A_4}\right)^2\right] \cdot \frac{v_R^3}{v_0^3} \quad (10)$$

Considering continuity equation: $A_1 v_0 = A_2 v_R \Leftrightarrow \frac{A_1}{A_2} = \frac{v_R}{v_0} \Leftrightarrow \left(\frac{A_1}{A_R}\right)^3 = \left(\frac{v_R}{v_0}\right)^3$

Resulting equation of the maximum performance coefficient of the diffuser augmented wind turbine for a given geometry is the following:

$$\boxed{c_{p,DAWT} = \left[\left(\frac{A_2}{A_1}\right)^2 - \left(\frac{A_3}{A_4}\right)^2\right] \cdot \left(\frac{A_1}{A_R}\right)^3} \quad (11)$$

Next step is to calculate area ratios to maximize the coefficient performance function using partial derivatives.

$$c_{p,DAWT} = \left[\left(\frac{A_R}{A_1}\right)^2 - \left(\frac{A_R}{A_4}\right)^2\right] \cdot \left(\frac{A_1}{A_R}\right)^3 = \frac{A_1^3 \cdot A_R^2}{A_1^2 \cdot A_R^3} - \frac{A_1^3 \cdot A_R^2}{A_4^2 \cdot A_R^3} = \frac{A_1}{A_R} - \frac{A_1^3}{A_4^2 A_R} = \frac{A_1}{A_R} \cdot \left(1 - \left(\frac{A_1}{A_4}\right)^2\right)$$

Let $\frac{A_1}{A_R} = a$ and $\frac{A_1}{A_4} = b$

$$\Rightarrow c_p = f\big(a(1 - b^2)\big) \quad (12)$$

$$f(a, b) = a(1 - b^2)$$

$$\frac{\partial f}{\partial a} = 1 - b^2$$

$$\frac{\partial f}{\partial b} = -2ab$$

$$\frac{\partial^2 f}{\partial a^2} = 0$$

$$\frac{\partial^2 f}{\partial b^2} = -2a$$

$$\frac{\partial^2 f}{\partial a \partial b} = -2b$$

Stationary points:

$$\frac{\partial f}{\partial a} = 0 \Leftrightarrow 1 - b^2 = 0 \Rightarrow b = \pm 1$$

$$\frac{\partial f}{\partial b} = 0 \Leftrightarrow -2ab = 0 \Rightarrow a = 0 \; or \; b = 0$$

Now there are two stationary points: $(0,1)$; $(0,-1)$

Check if these points are local maxima or minima:

$f_{aa} f_{bb} - f_{ab}^2 = 0 - 2 = -2$ <0 (however it is not local maxima since f_{aa} is not <0)

This function does not have either local maxima or local minima.

Since the overall optimization of the DAWT geometry based on the fluid mechanic equations and neglecting the rotor produced a solution, the different parts of the DAWT are analyzed individual in the following sections.

4.2 Geometry optimization

Diffuser-augmented wind turbine consists of the following geometrical parameters that can be manipulated in order to maximize the performance coefficient (and as a consequence, the power output): nozzle (inlet) area ratio, diffuser (outlet) area ratio, length of the nozzle and diffuser, opening angle of the nozzle and diffuser. Since the flow analysis did not yield meaningful area ratios, the literature review was used to define area ratios and subsequently adjust these parameters using Excel and results of the flow analysis.

The wind speeds from 5 km/h (1.89 m/s) till 60 km/h (16.67 m/s) are taken, step in between +3 km/h. Geometry optimization consists of the following steps performed in Excel (Appendix A):

1) For fixed wind speed, rotor diameter is varied between 0.05 m and 1.5 m in order to stay in the range of small wind turbine size
2) From rotor diameter, area of the rotor is calculated using the formula:

$$A_R = \pi \left(\frac{d_R}{2}\right)^2 \tag{13}$$

   With:
   A_R = Rotor area [m^2]
   d_R = rotor diameter [m]
3) The inlet area is calculated using the optimum ratio between inlet area and rotor area, which is equivalent to $\frac{d_{in}}{d_R}$ (corresponding to $\frac{d_1}{d_2}$ in the figure below). From the diagram below (Fig. 12), if the angle is too small, then in order to keep the area ratio, the length of the nozzle will be increased, which leads to friction losses. As a starting point, according to Rivarolo et al., the best nozzle performance achieved for the diameter ratio D_R/D_1 is taken as equal to 0.5, which is equivalent to $\frac{D_1}{D_R} = 2$.

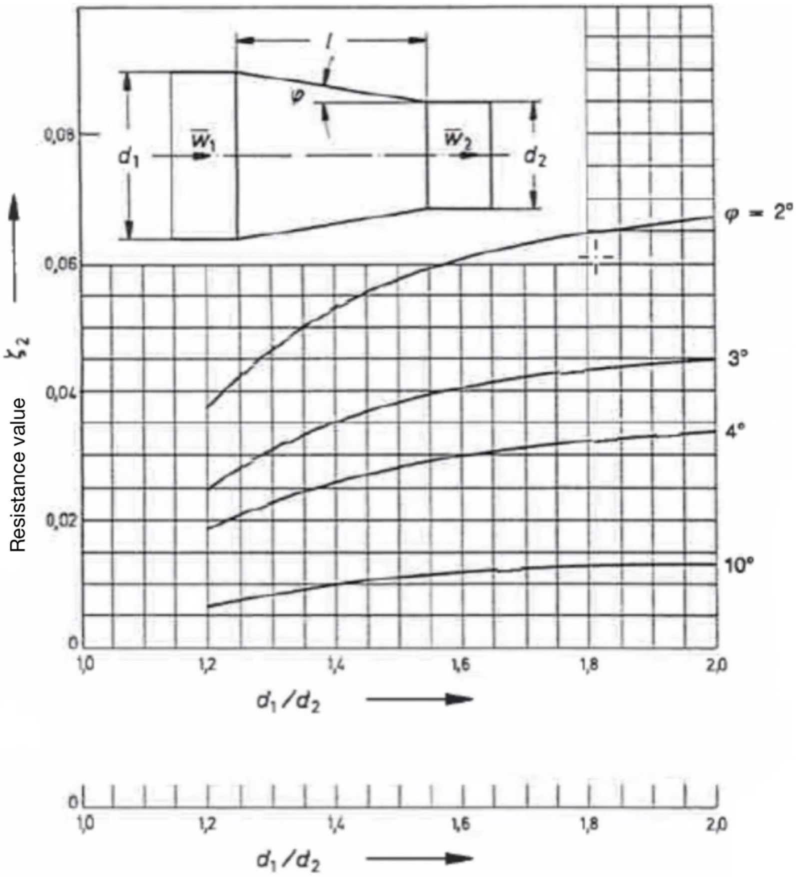

Figure 12: Resistance value of nozzle from VDI manual Energy Technology. Part 2. Heat workbook.

4) Further adjustments in Excel demonstrated that the maximum c_p of the diffuser-augmented wind turbine is achieved for $D_R/D_1 = 1.7$.
5) The next step is to calculate the inlet area using the inlet/rotor diameter ratio with the following formula:

$$A_{in} = \frac{A_{in}}{A_R} A_R = 1.7 \cdot A_R \tag{14}$$

With:
A_{in} = Nozzle inlet area [m^2]
6) The length of the nozzle was calculated using the basic trigonometrical principles, leading to the following formula:

$$L_{nozzle} = \frac{\frac{A_1}{A_R} - 1}{\frac{2}{d_R} \cdot \tan\alpha} \tag{15}$$

With:
L_{nozzle} = Length of the nozzle [m]
α = Opening angle of the nozzle [rad]
7) Using continuity equation v_R (flow velocity upstream in front of the rotor) was calculated:

$$v_R = \frac{A_{in} \cdot v_{wind}}{A_R} = \frac{A_{in}}{A_R} \cdot v_{wind} \tag{16}$$

With:

v_{wind} = Wind speed at the inlet of DAWT [m/s]

8) The diffusor geometry optimization is based on the diagram below by Kleine et al. (Fig. 13).

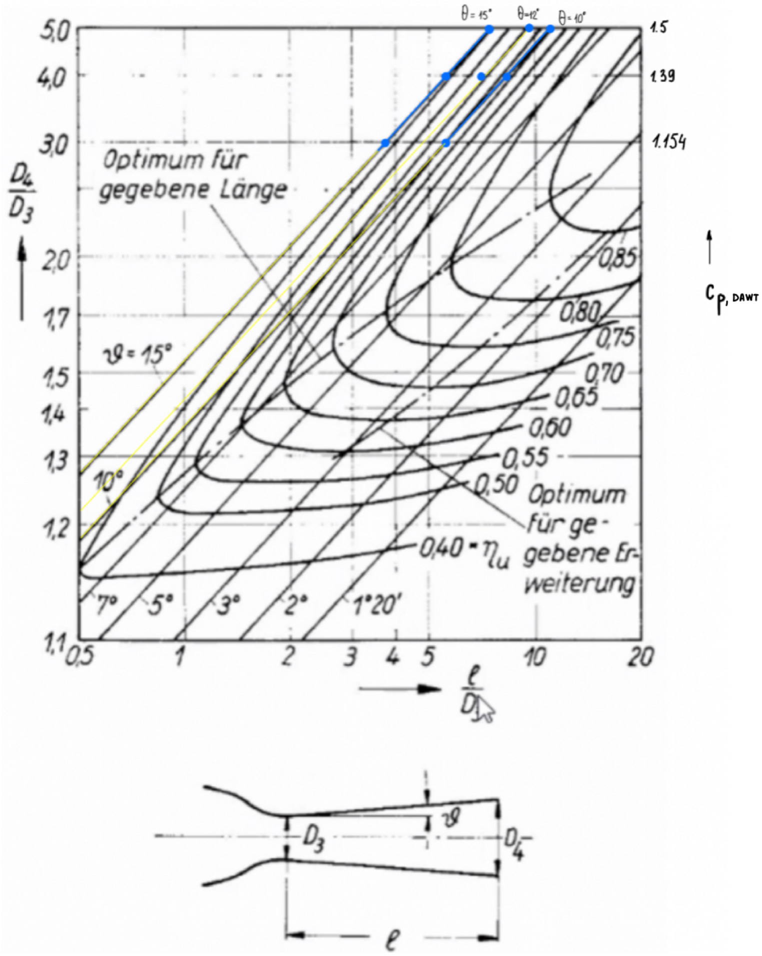

Figure 13: Diffuser diagram by Japikse et al.

Due to the danger of flow separation, not too large angles should be analyzed. Making several iterations for different diffuser opening angles, taking into account that it cannot be too small because it would increase the length of the wind turbine system and as a consequence, increase the friction losses, angles of 10°, 12°, and 15° were analyzed. The results of iterations are furnished in the Table 1.

With:

θ = full diffuser opening angle from figure 13 [°]

Table 1: Diffuser area ratio adjustment

A_4/A_R =3 θ=10° L_diff/d_R =6	$C\_(p, DAWT)$=1.154 (L_total=11.9 m)
A_4/A_R =3 θ=15° L_diff/d_R =4	$C\_(p, DAWT)$=1.154 (L_total=8.9 m)
A_4/A_R =4 θ=10° L_diff/d_R =8	$C\_(p, DAWT)$=1.39 (L_total=14.9 m)
A_4/A_R =4 θ=12° L_diff/d_R =7	$C\_(p, DAWT)$=1.39 (L_total=13.48 m)
A_4/A_R =4 θ=15° L_diff/d_R =6	$C\_(p, DAWT)$=1.39 (L_total=11.97 m)
A_4/A_R =5 θ=10° L_diff/d_R =11	$C\_(p, DAWT)$=1.5 (L_total= 19 m)
A_4/A_R =5 θ=12° L_diff/d_R =10	$C\_(p, DAWT)$=1.5 (L_total= 17.98 m)
A_4/A_R =5 θ=15° L_diff/d_R =7	$C\_(p, DAWT)$=1.5 (L_total= 13.48 m)

Green block represents diffuser parameters leading to maximum $c_{p,DAWT}$ value of 1.503 and total length of 13.48 m for maximum rotor diameter of 1.5 m.
Using figure 13 to optimize the diffuser only for a given length yields the following result:

For max $c_{p,dif}$ (read from the diagram 13):

- $\frac{D_{out}}{D_R} = 2.5$
- $\frac{L}{D_R} = 11$
- $\theta = 4°$

These parameters give the max. $c_{p,dif} = 0.85$; however, with same parameters (optimum for diffusor only) the system performance is 0.914, making the total length 19.477m

Using figure 13 to optimize the diffuser only for a given opening angle θ of diffuser gives the following result:

For max $c_{p,dif}$ (read from the diagram 13):

- $\frac{D_{out}}{D_R} = 2.2$
- $\frac{L}{D_R} = 16$
- $\theta = 2.1°$

These parameters give the max. $c_{p,dif} = 0.85$; however, with same parameters (optimum for diffusor only) the system performance is 0.685, making total length 26.977m.

Optimum diffusor numbers are not optimum for the entire system, because it decreases the system performance and increases the length of the system, as a consequence increasing friction losses.

Manipulating diffuser area ratio, length to rotor diameter ratio and diffuser opening angle led to the maximum coefficient of performance of diffuser-augmented wind turbine as a whole system of 1.503 for diffuser area ratio equal to 5, diffuser opening angle of 15 and $\frac{L_{diff}}{d_R} = 7$.

9) The output area is calculated using the formula:

$$A_{out} = 5A_R \tag{17}$$

With:
A_{out} = diffuser outlet area [m^2]

10) Diffuser length is calculated with optimum length to rotor diameter ratio of 7:

$$L_{diffusor} = 7D_R \tag{18}$$

11) Total length of the system is calculated summing up the nozzle and diffuser length.
12) Finally, performance coefficient of diffuser-augmented wind turbine is calculated using the formula derived in flow analysis chapter (Equation (11)). These parameters lead to performance coefficient of 1.503 and maximal total length of diffuser augmented wind turbine of 13.48 m.
13) Last two steps are to calculate the power of conventional wind turbine without shroud and diffuser-augmented wind turbine with nozzle and diffuser. The power of traditional wind turbine is calculated with:

$$P_{W.T.} = \frac{1}{2} c_{p\,(W.T.)} \rho A v_{wind}^3 \tag{19}$$

With:
$P_{W.T.}$ = Power of traditional wind turbine [W]
$c_{p\,(W.T.)}$ = performance coefficient of traditional wind turbine (=0.59)

The power of diffuser-augmented wind turbine is calculated with the same formula, but considering the velocity at the rotor and higher performance coefficient of 1.503 achieved by improved duct geometry:

$$P_{DAWT} = \frac{1}{2} c_{p,DAWT} \rho A v_R^3 \quad (20)$$

With:

P_{DAWT} = Power of diffuser-augmented wind turbine [W]

$c_{p,DAWT}$ = performance coefficient of diffuser augmented wind turbine (=1.503)

4.3 Comparison of conventional and diffuser augmented wind turbine in terms of performance and power output

Figure14 demonstrates the advantage of diffuser-augmented wind turbine, compared to traditional wind turbine. The y-axis represents power output in watts and y-axis rotor diameters from 0.05m up till 1.5m with step of 0.05m. Solid lines stands for diffuser-augmented wind turbines and dashed lines stand for conventional wind turbines. Same color of the curve means the same wind speed; for example, red solid line is power output of diffuser-augmented wind turbine at 16.67 m/s and red dashed line is power output of traditional wind turbine at 16.67 m/s. At the wind speed of 16.67 m/s, the maximal power output of the traditional wind turbine is 2970 W, while that of the diffuser-augmented wind turbine is 7560 W.

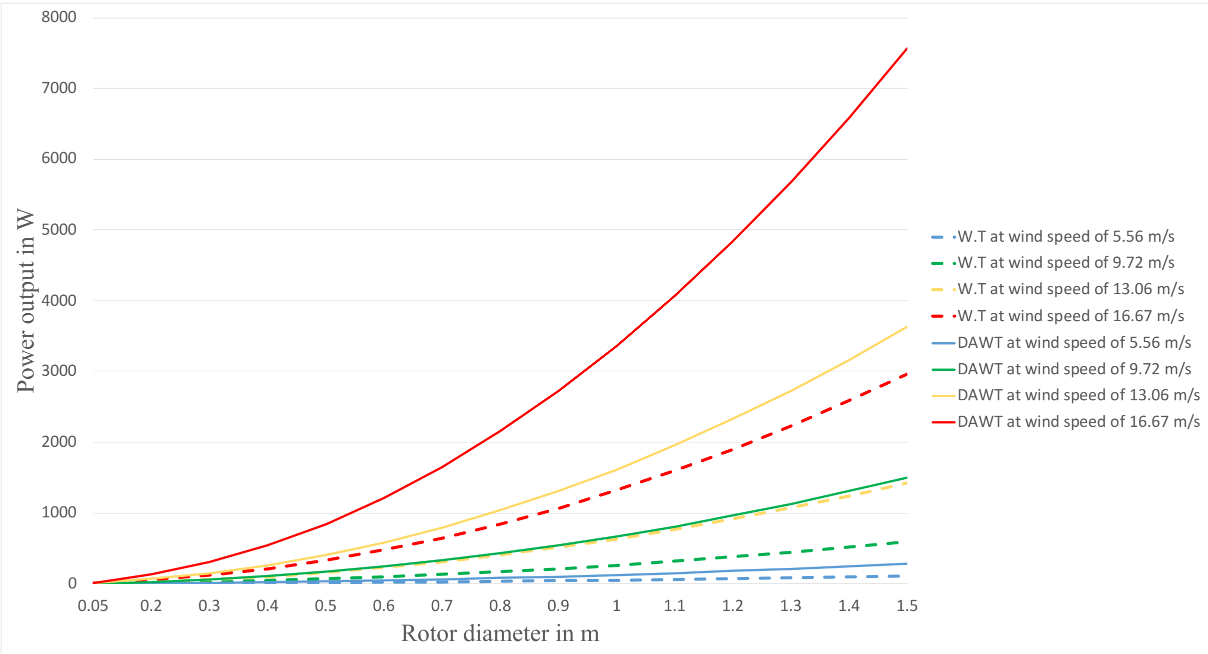

Figure 14: Power output of conventional wind turbine and DAWT as a function of wind speed & rotor diameter

This diagram clearly shows the advantage of the diffuser-augmented wind turbine in terms of performance.

Diagram 15 displays the power output as a function of rotor diameter at fixed wind speed of 5.56 m/s of both diffuser-augmented wind turbine and conventional wind turbine.

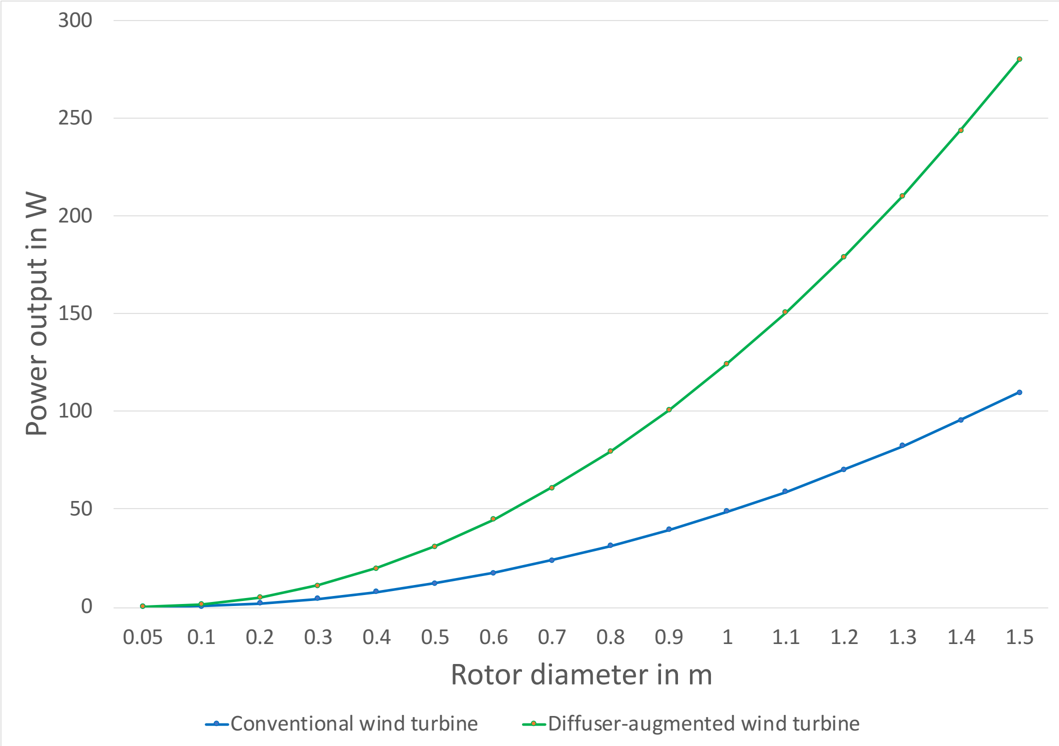

Figure 15: Power output as a function of rotor diameter for wind speed = 5.56 m/s

To have the better understanding of the advantage of diffuser augmented wind turbine the diameter of a conventional wind turbine was calculated, which will produce the same power output of DAWT depicted in Figure 15. (Fig. 16).

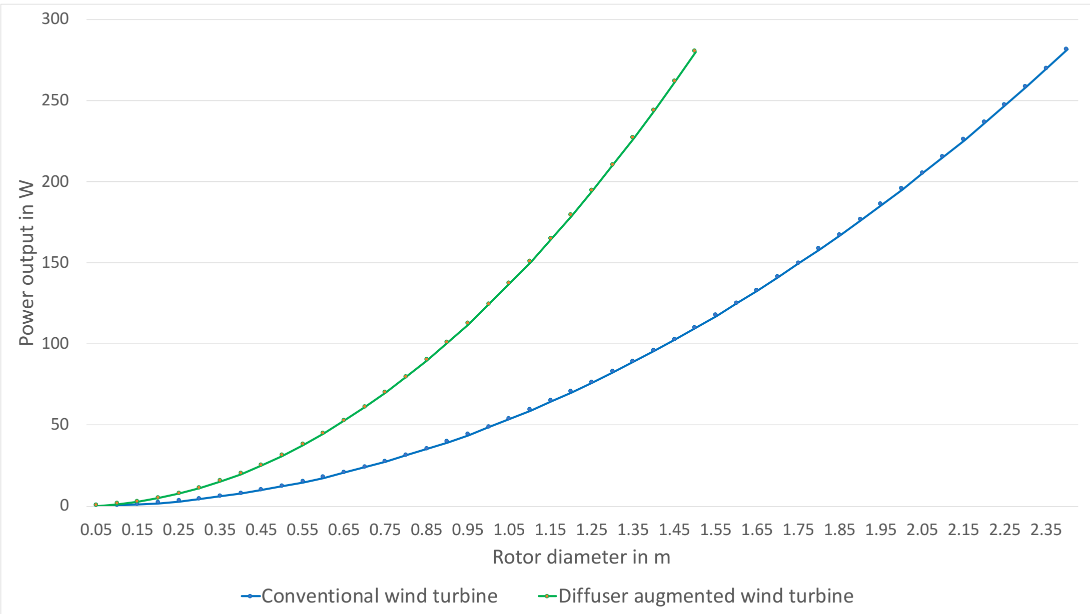

Figure 16: Power output as a function of rotor diameter for wind speed = 5.56 m/s comparing conventional wind turbine vs DAWT

The following four diagrams (Fig. 17) represent power output as a function of wind speed for different fixed rotor diameters of 0.1m, 0.5m, 1m, and 1.5m.

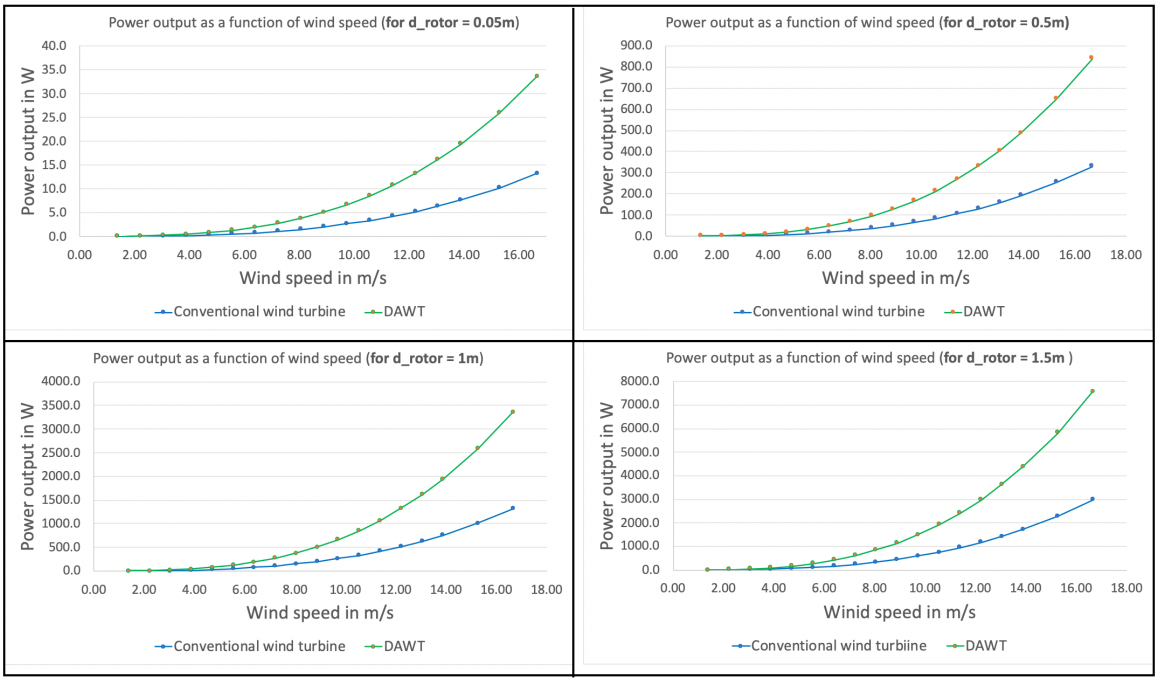

Figure 17: Power output as a function of wind speed for fixed rotor diameters (0.1m, 0.5m, 1m, 1.5m)

4.4 Comparison of results with previous studies

Ohya et al. (2010) studied the development of a wind power system with high output, to determine how to collect the wind energy efficiently and what kind of wind turbine can generate energy effectively from the wind. In the study, this concept of accelerating the wind was named the "wind-lens" technology. For this purpose, they developed a diffuser-type structure capable of collecting and accelerating the approaching wind. The results of the study in terms of performance coefficient are shown in the figure below (Fig. 18 & 19).

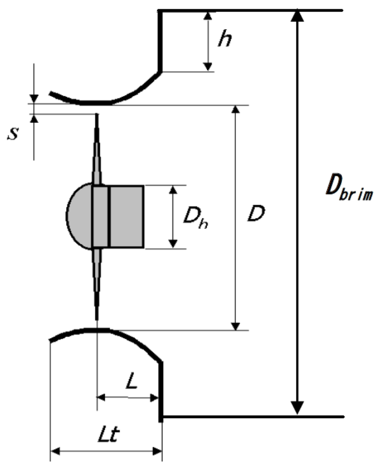

Figure 18: Schematic of wind-lens turbine by Ohya 2010

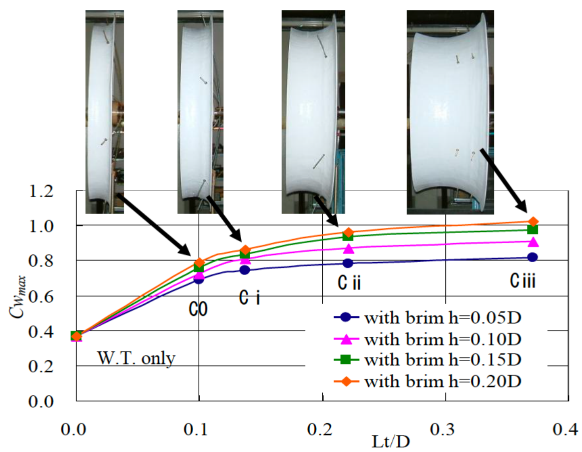

Figure 19: Maximum power output for different C-type wind-lens length by Ohya, 2010

The authors were able to achieve the maximum performance coefficient of 1.02 for the largest $\frac{L_t}{D} = 0.37$.

Another study focused on the development of a wind turbine system consisting of a diffuser shroud with a broad ring flange at the exit periphery and a wind turbine inside it. The flanged-diffuser shroud plays the role of a device for collecting and accelerating the approaching wind. Emphasis is placed on positioning the flange at the exit of a diffuser shroud, i.e. the flange generates a low-pressure region in the exit neighborhood of the diffuser by vortex formation and draws more mass flow to the wind turbine inside the diffuser shroud.

The feature that distinguishes this geometry of diffuser-augmented wind turbine from the others is a large flange attached at the exit of the diffuser shroud (Fig. 21).

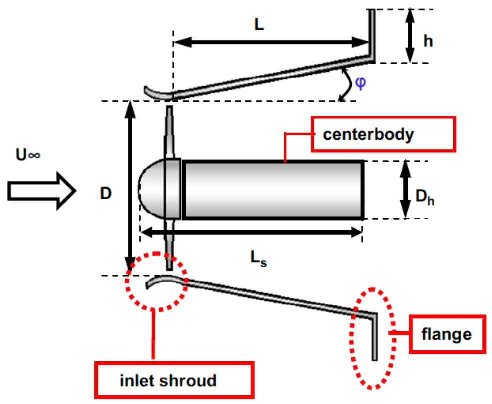

Figure 21: Schematic of a wind turbine equipped with a flanged diffuser shroud from development of a shrouded wind turbine with a flanged diffuser by Yuji et. al, 2008

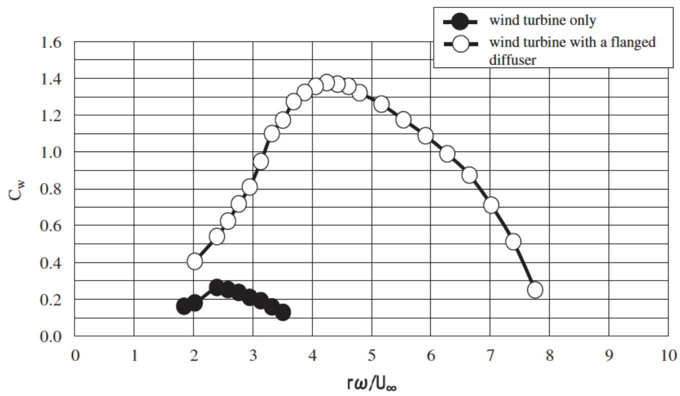

Figure 20: Comparison of power coefficients between the wind turbine equipped with a flanged diffuser and the standard (bare) wind turbine from development of a shrouded wind turbine with a flanged diffuser by Yuji et. al, 2008

Maximum power coefficient achieved with flange in this study is 1.39 (Fig. 20), which is very close to the maximal c_p result of the current study (Ohya, 2008).

One more example of earlier researches is a Computational Fluid Dynamics (CFD) Analysis of The City College of New York, considering not only the diffuser part, but both nozzle and diffuser parts (Sabri et al. 2017). Wind velocity of 5 m/s is taken. For each geometry the power available is:

$$P_{available} = \frac{1}{2} A\rho v^3 \tag{21}$$

With:

$P_{available}$ = Power available [W]

A = Inlet area [m^2]

v = wind speed [m/s]

Generated power was calculated using the formula:

$$P_{generated} = \tau\omega \tag{22}$$

With:

$P_{generated}$ = Power generated by the wind turbine [W]

τ = Torque [Nm]

ω = Angular velocity [rad/s]

The the power captured is defined calculated using the formula:

$$P_{captured} = \frac{P_{generated}}{P_{available}} \tag{23}$$

With:

$P_{captured}$ = Power captured by the wind turbine [W].

Thus, it is possible to compare the power captured of simple rotor and different diffuser-augmented wind turbine geometries demonstrated in figure 23.

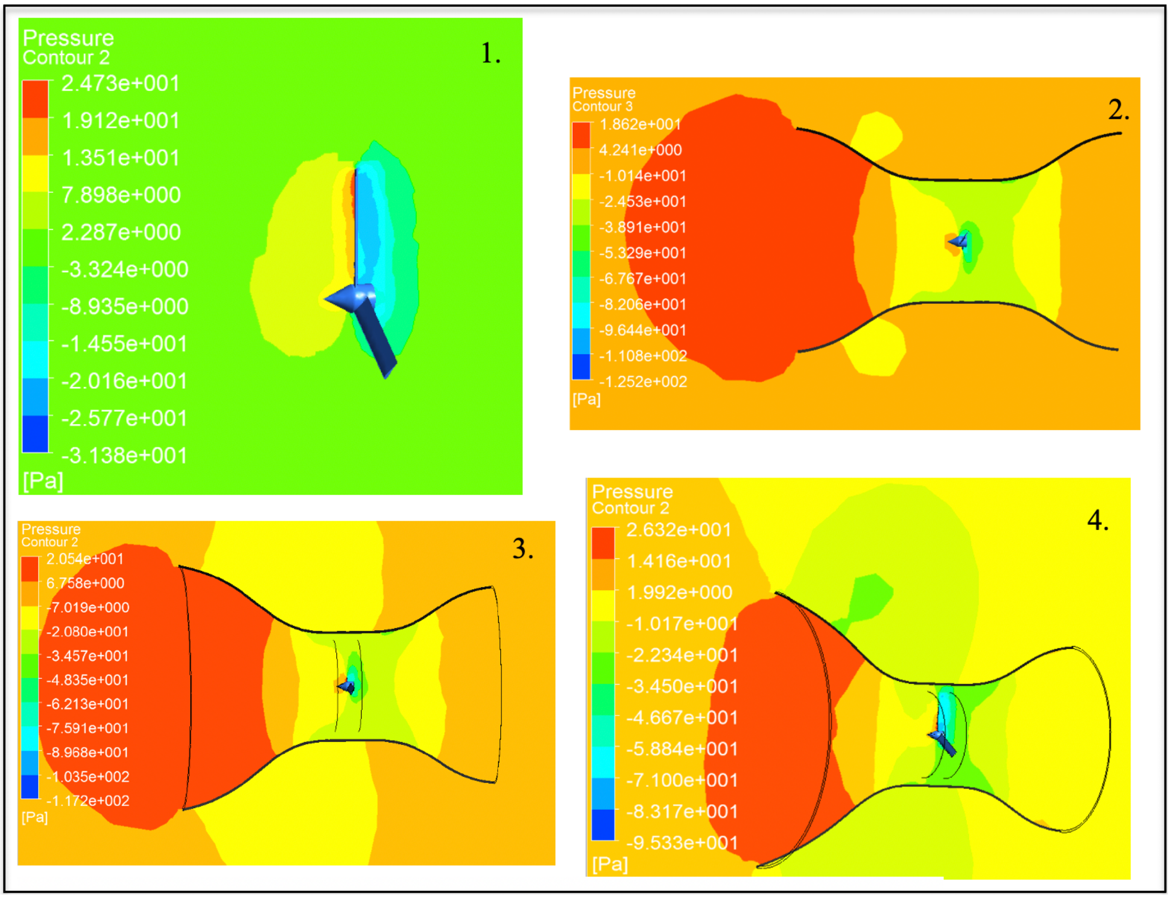

Figure 23: CFD results of different nozzle-diffuser systems analyzed from Logic Group HeroEasy

The first simulation is performed only for the rotor without the shroud and the calculation shows that only 2.85% of power is captured. In the second simulation, a simple and short nozzle and diffuser system are introduced around the rotor that results in 26% of power being captured. In the third simulation, the nozzle and diffuser areas are increased, which leads to 52.8% of captured power. Lastly, the nozzle and diffuser parts are extended that leads to 76.8% of captured power. The efficiency of the wind turbine improves with the introduction of the nozzle-diffuser system.

4.5 Economic aspect of diffuser augmented wind turbine in comparison to conventional wind turbine

In order to evaluate the approximate costs and compare the diffuser-augmented wind turbine with conventional wind turbine, the same wind speed and rotor diameter were considered. The costs are analyzed based on the power produced.

Small wind turbine generator for sale, 100-watt power, 3-bladed wind turbine, rated voltage 12-volt or 24-volt, high-quality aluminum alloy body, strong wind resistance costs $267.69 on ATO website. The specifications of the model are as per the table below (Table 2) and Figure 24:

Table 2: Characteristics of ATO small wind turbine from https://ato.com

Model	ATO-WT-S100
Rated Power	100W
Maximum Power	130W
Rated Voltage	12V/24V
Start Up Wind Speed	2.0 m/s
Rated Wind Speed	10 m/s
Survival Wind Speed	55 m/s
Wheel Diameter	1.2m
Blase Number	3/5
Blades Material	Nylon Fiber
Generator	Three Phase Permanent Magnet AC Generator
Magnetic Steel	NdFeB
Generator Case	Die-Casting Aluminum
Controller System	Electromahnet
Speed Regulation	Automatically Adjust Windard
Installation Flange	DN20
Working Temperature	-40°C~80°C
Gross Weight	8.5kg
Top Net Weight	6kg
Service Life	15 years
Warranty	18 months
Package Dimension	670*280*210mm

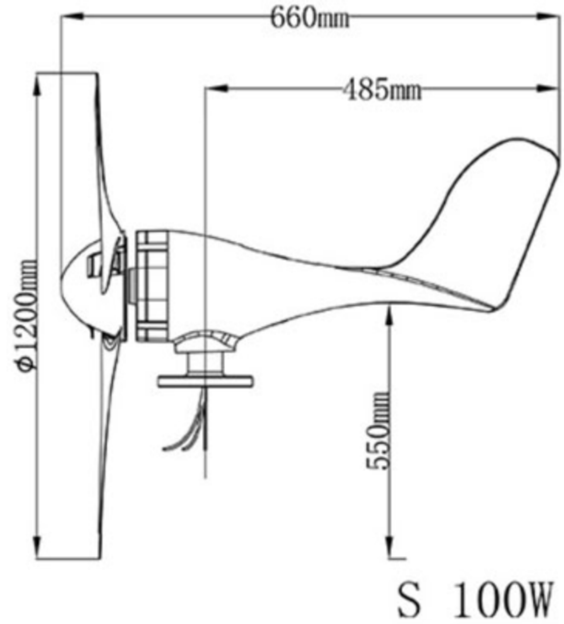

Figure 24: Traditional wind turbine dimensions for economic analysis from https://ato.com

With the same rotor diameter of 1.2m at the speed of 6.39 m/s, the diffuser-augmented wind turbine produces 296W, which is 66.2% more than the conventional wind turbine. The price of the same dimensions of diffuser-augmented wind turbine, at $321.23, is approximately 20% more than that of the traditional wind turbine, according to Dr. Alessabro Bianchini, professor and researcher in Firenze University.

According to "Global Wind Atlas" the average wind speed in Switzerland is around 5.5 m/s. Therefore, the power output is analyzed, which is at 5.56 m/s represented in Table 3.

Table 3: System parameters and power output for wind speed of 5.56 m/s

v_wind [km/h]	v_wind [m/s]	d_R [m]	A_R [m]	A_in [m]	L_noz [m]	v_R [m/s]	A_out [m]	L_dif [m]	L_total [m]	$C\_(p, DAWT)$		P_(W.T.) [W]	P_DAWT [W]
20	5.56	0.05	0.002	0.003	0.099	9.445	0.010	0.4	0.449	1.503		0.12	0.31
		0.10	0.008	0.013	0.198	9.445	0.039	0.7	0.898	1.503		0.49	1.24
		0.15	0.018	0.030	0.298	9.445	0.088	1.1	1.348	1.503		1.10	2.80
		0.20	0.031	0.053	0.397	9.445	0.157	1.4	1.797	1.503		1.95	4.98
		0.25	0.049	0.083	0.496	9.445	0.245	1.8	2.246	1.503		3.05	7.78
		0.30	0.071	0.120	0.595	9.445	0.353	2.1	2.695	1.503		4.40	11.20
		0.35	0.096	0.163	0.695	9.445	0.481	2.5	3.145	1.503		5.98	15.25
		0.40	0.126	0.214	0.794	9.445	0.628	2.8	3.594	1.503		7.81	19.91
		0.45	0.159	0.270	0.893	9.445	0.795	3.2	4.043	1.503		9.89	25.20
		0.50	0.196	0.334	0.992	9.445	0.981	3.5	4.492	1.503		12.21	31.12
		0.55	0.237	0.404	1.092	9.445	1.187	3.9	4.942	1.503		14.77	37.65
		0.60	0.283	0.480	1.191	9.445	1.413	4.2	5.391	1.503		17.58	44.81
		0.65	0.332	0.564	1.290	9.445	1.658	4.6	5.840	1.503		20.64	52.59
		0.70	0.385	0.654	1.389	9.445	1.923	4.9	6.289	1.503		23.93	60.99
		0.75	0.442	0.751	1.489	9.445	2.208	5.3	6.739	1.503		27.47	70.01
		0.80	0.502	0.854	1.588	9.445	2.512	5.6	7.188	1.503		31.26	79.66
		0.85	0.567	0.964	1.687	9.445	2.836	6.0	7.637	1.503		35.29	89.92
		0.90	0.636	1.081	1.786	9.445	3.179	6.3	8.086	1.503		39.56	100.81
		0.95	0.708	1.204	1.886	9.445	3.542	6.7	8.536	1.503		44.08	112.33
		1.00	0.785	1.335	1.985	9.445	3.925	7.0	8.985	1.503		48.84	124.46
		1.05	0.865	1.471	2.084	9.445	4.327	7.4	9.434	1.503		53.85	137.22
		1.10	0.950	1.615	2.183	9.445	4.749	7.7	9.883	1.503		59.10	150.60
		1.15	1.038	1.765	2.283	9.445	5.191	8.1	10.333	1.503		64.59	164.60
		1.20	1.130	1.922	2.382	9.445	5.652	8.4	10.782	1.503		70.33	179.22
		1.25	1.227	2.085	2.481	9.445	6.133	8.8	11.231	1.503		76.31	194.47
		1.30	1.327	2.255	2.580	9.445	6.633	9.1	11.680	1.503		82.54	210.34
		1.35	1.431	2.432	2.680	9.445	7.153	9.5	12.130	1.503		89.01	226.83
		1.40	1.539	2.616	2.779	9.445	7.693	9.8	12.579	1.503		95.73	243.94
		1.45	1.650	2.806	2.878	9.445	8.252	10.2	13.028	1.503		102.69	261.68
		1.50	1.766	3.003	2.977	9.445	8.831	10.5	13.477	1.503		109.89	280.04

In order to define the prices of traditional wind turbines, the known prices of small wind turbines are extrapolated and approximated for necessary power output. Considering that a 100W conventional wind turbine costs $267.69, dividing it by 100 and gives us the price of $2.677 per watt. The following table is calculated at the wind speed of 5.56 m/s for different rotor diameters:

Table 4: Wind turbine prices for different rotor diameters at wind speed of 5.56 m/s

d_R [m]	P_(W.T.) [W]	Price_W.T. [$]		P_DAWT [W]	Price_DAWT [$]
0.05	0.12	0.33		0.31	0.39
0.10	0.49	1.31		1.24	1.57
0.15	1.10	2.94		2.80	3.53
0.20	1.95	5.23		4.98	6.28
0.25	3.05	8.17		7.78	9.81
0.30	4.40	11.77		11.20	14.12
0.35	5.98	16.02		15.25	19.22
0.40	7.81	20.92		19.91	25.10
0.45	9.89	26.48		25.20	31.77
0.50	12.21	32.69		31.12	39.22
0.55	14.77	39.55		37.65	47.46
0.60	17.58	47.07		44.81	56.48
0.65	20.64	55.24		52.59	66.29
0.70	23.93	64.06		60.99	76.88
0.75	27.47	73.54		70.01	88.25
0.80	31.26	83.68		79.66	100.41
0.85	35.29	94.46		89.92	113.36
0.90	39.56	105.90		100.81	127.08
0.95	44.08	118.00		112.33	141.60
1.00	48.84	130.74		124.46	156.89
1.05	53.85	144.15		137.22	172.97
1.10	59.10	158.20		150.60	189.84
1.15	64.59	172.91		164.60	207.49
1.20	70.33	188.27		179.22	225.93
1.25	76.31	204.29		194.47	245.15
1.30	82.54	220.96		210.34	265.15
1.35	89.01	238.28		226.83	285.94
1.40	95.73	256.26		243.94	307.51
1.45	102.69	274.89		261.68	329.87
1.50	109.89	294.17		280.04	353.01

To be able to compare conventional wind turbine and diffuser-augmented wind turbine from economic point of view, the same wind speed and power output is considered ($v_{wind} = 5.56\ m/s$ and $P_{out} = 280\ W$). Diffuser augmented produces this power output with rotor diameter of 1.5 m and costs $353. On the other hand, conventional wind turbine needs the rotor diameter of 2.4 m, from figure16, to produce the same power output and costs $753. The price of conventional wind turbine to produce the same power output increases twice in comparison to diffuser-augmented wind turbine.

4.6 Diffuser augmented challenges and potential solutions

One of the major challenges is changing wind direction. The position of the diffuser-augmented wind turbine is fixed and when the wind direction changes, the turbine stops producing power.

Even when the wind blows perpendicular to the nozzle inlet surface, there is a boundary layer effect because of the earth and house, which are an obstacle in this layout (Lerch, 2018). In addition, the calculations are performed for wind velocity, which is represented by the red sector in Figure 25, while in reality, in the best-case scenario, only the light blue sector wind speed reaches the wind turbine inlet. The typical heights where the small wind turbine can be placed, for example at the top of the roof the wind velocity, are smaller because of the boundary layer effect.

Figure 25: Wind speed profile by Lerch et. al

In case the wind turbine is set on the roof of the house, wind movement vectors look as in Figure 26. The challenge is to choose the positioning of the turbine, because the direction of the wind along the roof is changing. At the beginning of the roof, the wind blows almost vertically upwards, progressively getting parallel to the inclined roof. A more detailed picture can be seen in Figure 27 below. The picture shows the wind direction for the cascade system of small wind turbines; however, the wind profile remains the same for a single turbine.

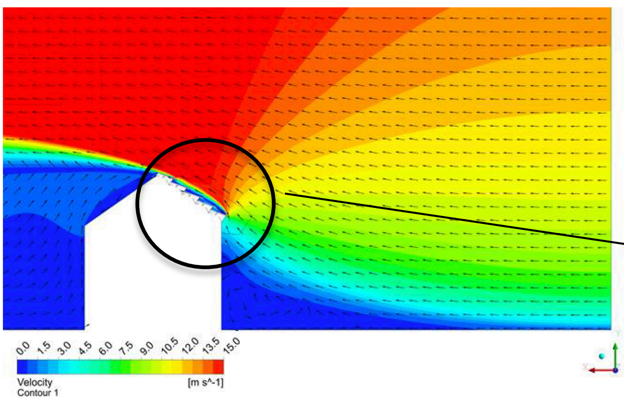

Figure 27: Wind direction vectors around the house by Lerch et. al

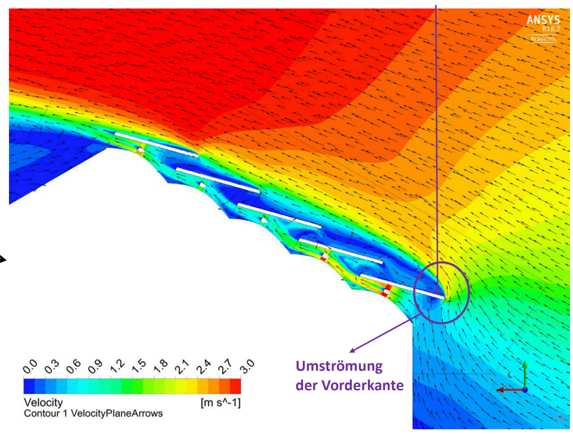

Figure 26: Wind direction vectors along the roof of the house by Lerch et. al

As can be seen in Figure 27, the magnitude of the vectors going inside of the wind turbine is significantly smaller than those going along the outer-surface of the turbine (Lerch, 2018).

A recently developed technology, INVELOX (increased velocity), has shown promise. (Allaei, 2013). The patented INVELOX is simply a wind capturing and delivery system that allows more engineering control than ever before (Allaei, 2012) While conventional wind turbines use massive turbine-generator systems mounted on top of a tower, INVELOX, by contrast, funnels wind energy to ground-based generators. Instead of snatching bits of energy from the wind as it passes through the blades of a rotor, the INVELOX technology captures wind with a funnel and directs it through a tapering passageway that passively and naturally accelerates its flow. This stream of wind energy then drives a generator that is installed safely and economically at ground or sub-ground levels.

The five key parts of INVELOX are showed in Fig. 28. These key parts are (1) intake, (2) pipe carrying and accelerating wind, (3) boosting wind speed by a Venturi, (4) wind energy conversions system, and (5) a diffuser.

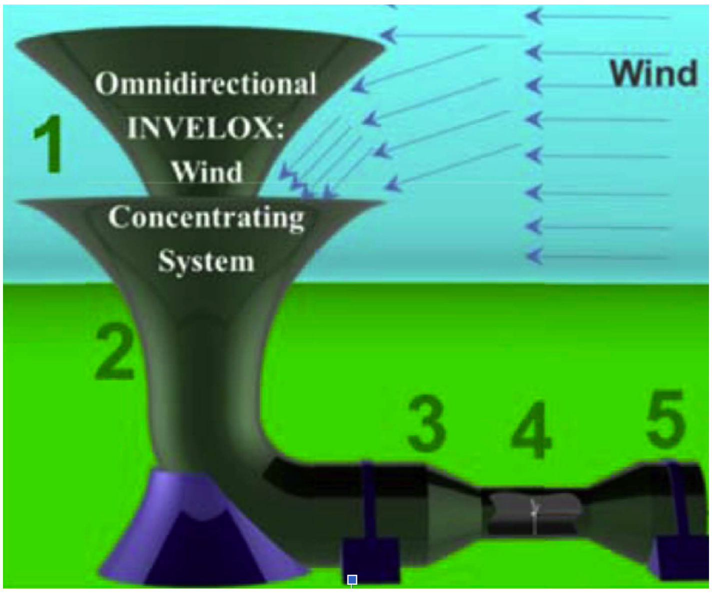

Figure 28: Schematic of the INVELOX wind delivery system from INVELOX: Description of a new concept in wind power and its performance evaluation by Allaei

The fundamental characteristic of the INVELOX system is that it captures a large portion of free stream air flow and can do so in nearly any free stream location with flow greater than 1 m/s. Another challenge of the diffuser-augmented wind turbine is the tendency of the wind to go around obstacles, because small DAWT are perceived as obstacles. An experiment was conducted for measuring the wind speed at the inlet, position 2 in figure below and close to the wall around the nozzle inlet, position 3 (Fig. 27) (Table 5) (Burg, 2018).

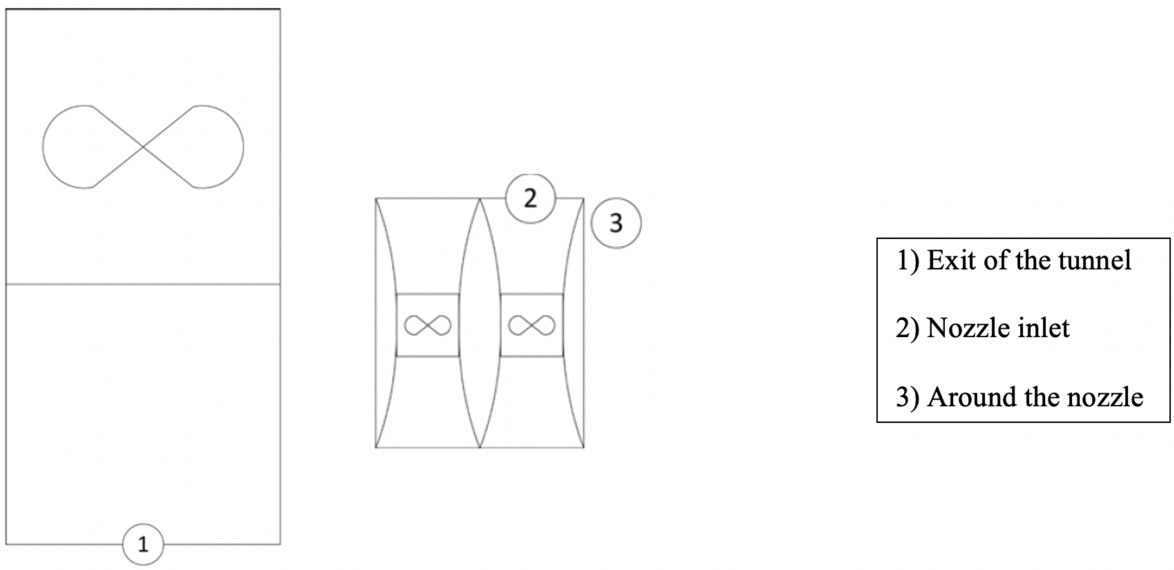

Figure 29: Schematic of wind tunnel with wind speed measuring positions

Table 5: Wind speed measurements at different positions

MP/Pos	w_1 [m/s]	w_2 [m/s]	w_3 [m/s]
1	17	5	20
2	10	3	13

Even if the flow matches the inlet of the diffuser-augmented wind turbine, the flow takes the path of minimum resistance. At the nozzle inlet is the blockage, because the area is limited. Another blockage is the rotor at the end of the nozzle; if there are too many losses at the nozzle inlet, it will have a negative effect on the suction.

5 Discussion of results

The first idea of the study was to optimize the diffuser augmented wind turbine through mathematical approach, but optimum c_p equations could not be solved because some upstream and downstream elements like the rotor, inlet Mach number, inlet blockage, etc. are missing. Therefore, another approach was used: nozzle and diffuser were treated separately, focusing on other studies, fluid dynamic principles, and available diagrams, finding optimum area and angle ratios separately and then combining and manipulating the data to get maximal performance coefficient of the diffuser-augmented wind turbine.

This technology is more beneficial where the wind direction is more or less constant at least over nights, because the system is stable and does not change its position according to the wind direction.

The results of both the previous studies that were compared to that of this study do not consider the nozzle and therefore lose the wind velocity gain entering the rotor, which leads to a smaller performance coefficient.

Comparison of the results of this study and results of field measurements show and validate that the diffuser-augmented wind turbine has a significant impact on the power output. Results of this study and results of the field measurement are displayed in Figures 30 and 31 respectively.

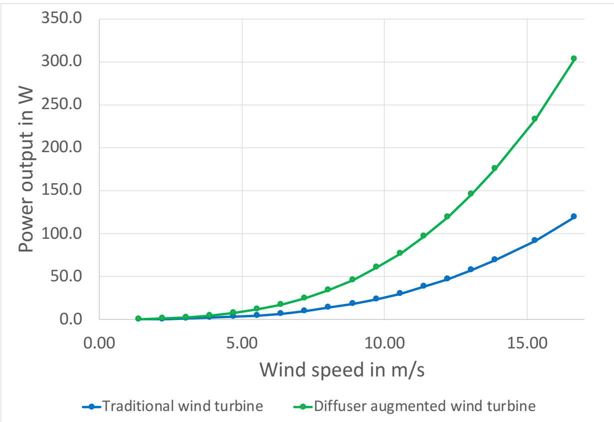

Figure 30: Power output for increasing wind speed at rotor diameter of 0.3m

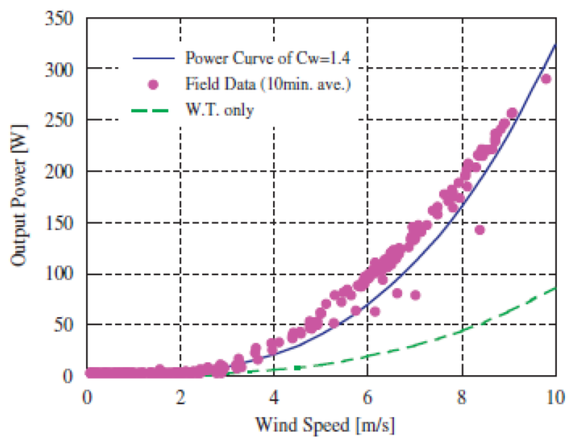

Figure 31: Power output as a function of wind speed by Ohya et. al

Changing wind direction represents a major challenge, as the wind turbine is fixed; and when the wind changes direction, the turbine ceases to produce power.

The tendency of the wind to go around obstacles represents another challenge for diffuser-augmented wind turbines, as small DAWT represent such obstacles. (Rephrase) Hence, in order to capture the incoming air, the larger nozzle inlet area has to be introduced to keep the area ratios. For the maximum performance, coefficient the nozzle diffuser system length increases, in which case the turbine ceases to be small-scale and cannot be used for a single-family house in the garden or on the roof.

Optimizing the diffuser is not a perfect solution, as the nozzle and diffuser have to be optimized simultaneously. Optimum parameters of the diffuser are based on analytical calculations, where the size effect is not considered. If the size of the diffuser is increased, as the calculations have shown, the optimum diffuser geometry implies a long resulting diffuser part, which leads to an increase in the friction losses.

6 Conclusions

Figure 32 shows c_p values of the rotor depending on the diffuser area ratio. Depending on the literature, the back pressure and on researchers, there are different c_p values and compared to their results, the outcome of this study with 1.503 is meaningful.

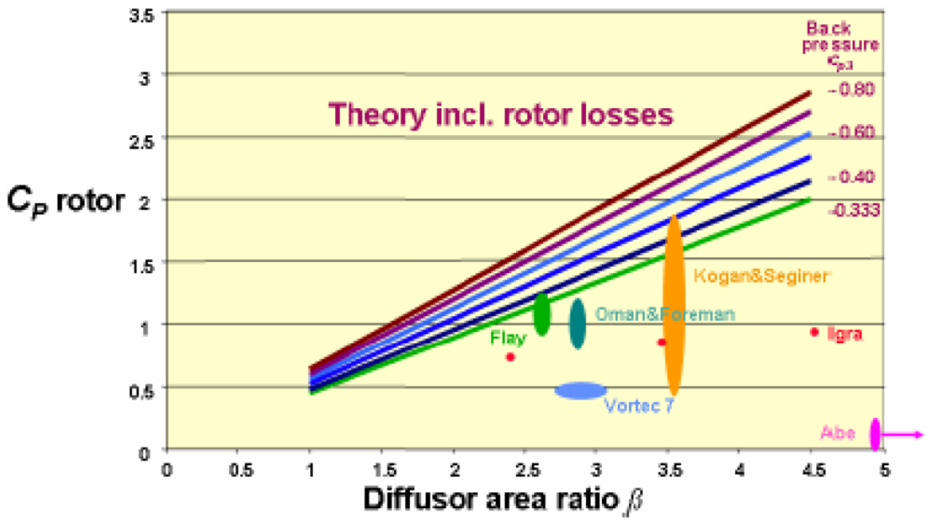

Figure 32: Comparison of theoretical achievable c_p-rotor values as a function of the DAWT area ratio with various experiments from *HERO Easy Modul – CFD Berechnungen für die Firma Logic Group*

Economic analysis clearly shows that if the diffuser-augmented wind turbine size is not too small, there is the size range where the diffuser-augmented wind turbine is advantageous in terms of $c_{p,DAWT}$, compared to the traditional wind turbine without any shroud, consisting of a rotor exclusively. The Betz value is a factor of 3 larger. This is shown by analysis as well as by previous test data. Making the nozzle-diffuser increases the costs by 20% but increase of performance coefficient and the output power for the same rotor diameter and wind velocities can be justified.

Optimization both c_p and $c_{p\ total}$ showed an increase in performance when compare to a Betz's limit for an open rotor. The results of the study show that optimum parameters of diffuser augmented wind turbine consisting of nozzle and diffuser parts are the following:

- $\frac{A_1}{A_R}$ (equivalent to $\frac{A_{in}}{A_R}$) =1.7
- $\frac{A_4}{A_R}$ (equivalent to $\frac{A_{out}}{A_R}$) = 5
- $\alpha = 10°$
- $\theta = 15°$
- $\frac{L_{diff}}{d_R} = 7$

These parameters give the maximum performance coefficient of the nozzle-diffuser wind turbine system of 1.503 and resulting length of 13.48 m with rotor diameter of 1.5 m.

The diffuser-augmented wind turbine with a nozzle and diffuser parts is provided in this thesis. Based on the recommendations offered in this thesis in terms of length, area ratio and opening angle, an optimum diffuser-augmented wind turbine can be designed, with higher performance than a conventional wind turbine of the same rotor size and wind speed. On the other hand, having this geometry will create a major problem in capturing the inlet wind. If the wind direction is changing, this system will not work. One solution could be INVELOX, a system that captures a large portion of free stream air flow and can do so in nearly any free stream location. The second option is to focus on short nozzle and diffuser around the rotor to overcome the problem of capturing the wind, despite a portion of the performance being lost.

According to the study of Rivarolo et al. the optimum nozzle area ratio is ½ to achieve the maximum wind velocity gain which is equivalent to 2 that is very close to the optimum of this study ($\frac{A_{inlet}}{A_R} = 1.7$). The study of Phillips concluded that the optimum diffuser area ratio has a value of around 3 in order to get maximum augmentation which is smaller than the result of this study that comes up with the value of $\frac{A_{out}}{A_R} = 5$. This difference is consequence of different assumptions and methods applied in the studies. This study takes into account all geometrical parameters like nozzle area ratio, diffuser area ratio, length, opening angles. In the study of Philipps diffuser area ratio was analyzed as a function of exit pressure coefficient, velocity speed up, free-stream, and local disc loading coefficient.

7 Recommendations

It is concluded that the current parameters could be used in the design for the initial configuration of diffuser augmented wind turbines. Although, more validation is needed, the calculated performance coefficient is relatively accurate comparing with previous studies and experiments which could yield to a valuable design tool for DAWTs.

Viscous effects are not taken into account with the current method and are a significant factor in the performance of a DAWT. Viscous effects could cause separation from the duct effectively squeezing the flow and minimizing the low-pressure region behind the rotor. Viscous effects could be taken into account using various boundary layer methods to calculate the displacement thickness and use that as the stream tube boundary in the design iteration. It is recommended that further research is done considering viscous effects and particularly the flow separation using CFD.

In order to solve the mathematical equation, we need the connection between upstream and downstream, nozzle and diffuser, which means that the rotor should be considered.

Further research should be also conducted on the captured wind of the optimum parameters on nozzle and diffuser parts defined in this research, to clarify whether performance gain is not ignored because of wind overtaking the system and not reaching the rotor. Future research can also focus on applying INVELOX inlet geometry to capture the wind and test it.

The short nozzle-diffuser system can be evaluated in terms of wind velocity gain, captured wind and prices.

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Appendices

Appendix A: Computation of power output of conventional and diffuser augmented wind turbines at different wind speeds

v_wind [km/h]	v_wind [m/s]	d_R [m]	A_R [m]	A_in [m]	L_noz [m]	v_R [m/s]	A_out [m]	L_dif [m]	L_total [m]	C_(p, DAWT)		P_(W.T.) [W]	P_DAWT [W]
5	1.39	0.05	0.002	0.003	0.099	2.361	0.010	0.4	0.449	1.503		0.00	0.00
		0.10	0.008	0.013	0.198	2.361	0.039	0.7	0.898	1.503		0.01	0.02
		0.15	0.018	0.030	0.298	2.361	0.088	1.1	1.348	1.503		0.02	0.04
		0.20	0.031	0.053	0.397	2.361	0.157	1.4	1.797	1.503		0.03	0.08
		0.25	0.049	0.083	0.496	2.361	0.245	1.8	2.246	1.503		0.05	0.12
		0.30	0.071	0.120	0.595	2.361	0.353	2.1	2.695	1.503		0.07	0.18
		0.35	0.096	0.163	0.695	2.361	0.481	2.5	3.145	1.503		0.09	0.24
		0.40	0.126	0.214	0.794	2.361	0.628	2.8	3.594	1.503		0.12	0.31
		0.45	0.159	0.270	0.893	2.361	0.795	3.2	4.043	1.503		0.15	0.39
		0.50	0.196	0.334	0.992	2.361	0.981	3.5	4.492	1.503		0.19	0.49
		0.55	0.237	0.404	1.092	2.361	1.187	3.9	4.942	1.503		0.23	0.59
		0.60	0.283	0.480	1.191	2.361	1.413	4.2	5.391	1.503		0.27	0.70
		0.65	0.332	0.564	1.290	2.361	1.658	4.6	5.840	1.503		0.32	0.82
		0.70	0.385	0.654	1.389	2.361	1.923	4.9	6.289	1.503		0.37	0.95
		0.75	0.442	0.751	1.489	2.361	2.208	5.3	6.739	1.503		0.43	1.09
		0.80	0.502	0.854	1.588	2.361	2.512	5.6	7.188	1.503		0.49	1.24
		0.85	0.567	0.964	1.687	2.361	2.836	6.0	7.637	1.503		0.55	1.41
		0.90	0.636	1.081	1.786	2.361	3.179	6.3	8.086	1.503		0.62	1.58
		0.95	0.708	1.204	1.886	2.361	3.542	6.7	8.536	1.503		0.69	1.76
		1.00	0.785	1.335	1.985	2.361	3.925	7.0	8.985	1.503		0.76	1.94
		1.05	0.865	1.471	2.084	2.361	4.327	7.4	9.434	1.503		0.84	2.14
		1.10	0.950	1.615	2.183	2.361	4.749	7.7	9.883	1.503		0.92	2.35
		1.15	1.038	1.765	2.283	2.361	5.191	8.1	10.333	1.503		1.01	2.57
		1.20	1.130	1.922	2.382	2.361	5.652	8.4	10.782	1.503		1.10	2.80
		1.25	1.227	2.085	2.481	2.361	6.133	8.8	11.231	1.503		1.19	3.04
		1.30	1.327	2.255	2.580	2.361	6.633	9.1	11.680	1.503		1.29	3.29
		1.35	1.431	2.432	2.680	2.361	7.153	9.5	12.130	1.503		1.39	3.54
		1.40	1.539	2.616	2.779	2.361	7.693	9.8	12.579	1.503		1.50	3.81
		1.45	1.650	2.806	2.878	2.361	8.252	10.2	13.028	1.503		1.60	4.09
		1.50	1.766	3.003	2.977	2.361	8.831	10.5	13.477	1.503		1.72	4.38
8	2.22	0.05	0.002	0.003	0.099	3.778	0.010	0.4	0.449	1.503		0.01	0.02
		0.10	0.008	0.013	0.198	3.778	0.039	0.7	0.898	1.503		0.03	0.08
		0.15	0.018	0.030	0.298	3.778	0.088	1.1	1.348	1.503		0.07	0.18
		0.20	0.031	0.053	0.397	3.778	0.157	1.4	1.797	1.503		0.13	0.32
		0.25	0.049	0.083	0.496	3.778	0.245	1.8	2.246	1.503		0.20	0.50
		0.30	0.071	0.120	0.595	3.778	0.353	2.1	2.695	1.503		0.28	0.72
		0.35	0.096	0.163	0.695	3.778	0.481	2.5	3.145	1.503		0.38	0.98
		0.40	0.126	0.214	0.794	3.778	0.628	2.8	3.594	1.503		0.50	1.27
		0.45	0.159	0.270	0.893	3.778	0.795	3.2	4.043	1.503		0.63	1.61
		0.50	0.196	0.334	0.992	3.778	0.981	3.5	4.492	1.503		0.78	1.99
		0.55	0.237	0.404	1.092	3.778	1.187	3.9	4.942	1.503		0.95	2.41
		0.60	0.283	0.480	1.191	3.778	1.413	4.2	5.391	1.503		1.13	2.87
		0.65	0.332	0.564	1.290	3.778	1.658	4.6	5.840	1.503		1.32	3.37
		0.70	0.385	0.654	1.389	3.778	1.923	4.9	6.289	1.503		1.53	3.90
		0.75	0.442	0.751	1.489	3.778	2.208	5.3	6.739	1.503		1.76	4.48
		0.80	0.502	0.854	1.588	3.778	2.512	5.6	7.188	1.503		2.00	5.10
		0.85	0.567	0.964	1.687	3.778	2.836	6.0	7.637	1.503		2.26	5.76
		0.90	0.636	1.081	1.786	3.778	3.179	6.3	8.086	1.503		2.53	6.45
		0.95	0.708	1.204	1.886	3.778	3.542	6.7	8.536	1.503		2.82	7.19
		1.00	0.785	1.335	1.985	3.778	3.925	7.0	8.985	1.503		3.13	7.97
		1.05	0.865	1.471	2.084	3.778	4.327	7.4	9.434	1.503		3.45	8.78
		1.10	0.950	1.615	2.183	3.778	4.749	7.7	9.883	1.503		3.78	9.64
		1.15	1.038	1.765	2.283	3.778	5.191	8.1	10.333	1.503		4.13	10.53
		1.20	1.130	1.922	2.382	3.778	5.652	8.4	10.782	1.503		4.50	11.47
		1.25	1.227	2.085	2.481	3.778	6.133	8.8	11.231	1.503		4.88	12.45
		1.30	1.327	2.255	2.580	3.778	6.633	9.1	11.680	1.503		5.28	13.46
		1.35	1.431	2.432	2.680	3.778	7.153	9.5	12.130	1.503		5.70	14.52
		1.40	1.539	2.616	2.779	3.778	7.693	9.8	12.579	1.503		6.13	15.61
		1.45	1.650	2.806	2.878	3.778	8.252	10.2	13.028	1.503		6.57	16.75
		1.50	1.766	3.003	2.977	3.778	8.831	10.5	13.477	1.503		7.03	17.92
11	3.06	0.05	0.002	0.003	0.099	5.194	0.010	0.4	0.449	1.503		0.02	0.05
		0.10	0.008	0.013	0.198	5.194	0.039	0.7	0.898	1.503		0.08	0.21
		0.15	0.018	0.030	0.298	5.194	0.088	1.1	1.348	1.503		0.18	0.47
		0.20	0.031	0.053	0.397	5.194	0.157	1.4	1.797	1.503		0.33	0.83
		0.25	0.049	0.083	0.496	5.194	0.245	1.8	2.246	1.503		0.51	1.29
		0.30	0.071	0.120	0.595	5.194	0.353	2.1	2.695	1.503		0.73	1.86
		0.35	0.096	0.163	0.695	5.194	0.481	2.5	3.145	1.503		1.00	2.54
		0.40	0.126	0.214	0.794	5.194	0.628	2.8	3.594	1.503		1.30	3.31
		0.45	0.159	0.270	0.893	5.194	0.795	3.2	4.043	1.503		1.65	4.19
		0.50	0.196	0.334	0.992	5.194	0.981	3.5	4.492	1.503		2.03	5.18
		0.55	0.237	0.404	1.092	5.194	1.187	3.9	4.942	1.503		2.46	6.26
		0.60	0.283	0.480	1.191	5.194	1.413	4.2	5.391	1.503		2.93	7.45
		0.65	0.332	0.564	1.290	5.194	1.658	4.6	5.840	1.503		3.43	8.75
		0.70	0.385	0.654	1.389	5.194	1.923	4.9	6.289	1.503		3.98	10.15
		0.75	0.442	0.751	1.489	5.194	2.208	5.3	6.739	1.503		4.57	11.65
		0.80	0.502	0.854	1.588	5.194	2.512	5.6	7.188	1.503		5.20	13.25
		0.85	0.567	0.964	1.687	5.194	2.836	6.0	7.637	1.503		5.87	14.96
		0.90	0.636	1.081	1.786	5.194	3.179	6.3	8.086	1.503		6.58	16.77
		0.95	0.708	1.204	1.886	5.194	3.542	6.7	8.536	1.503		7.33	18.69
		1.00	0.785	1.335	1.985	5.194	3.925	7.0	8.985	1.503		8.13	20.71
		1.05	0.865	1.471	2.084	5.194	4.327	7.4	9.434	1.503		8.96	22.83
		1.10	0.950	1.615	2.183	5.194	4.749	7.7	9.883	1.503		9.83	25.06
		1.15	1.038	1.765	2.283	5.194	5.191	8.1	10.333	1.503		10.75	27.39
		1.20	1.130	1.922	2.382	5.194	5.652	8.4	10.782	1.503		11.70	29.82
		1.25	1.227	2.085	2.481	5.194	6.133	8.8	11.231	1.503		12.70	32.36
		1.30	1.327	2.255	2.580	5.194	6.633	9.1	11.680	1.503		13.73	35.00
		1.35	1.431	2.432	2.680	5.194	7.153	9.5	12.130	1.503		14.81	37.74
		1.40	1.539	2.616	2.779	5.194	7.693	9.8	12.579	1.503		15.93	40.59
		1.45	1.650	2.806	2.878	5.194	8.252	10.2	13.028	1.503		17.08	43.54
		1.50	1.766	3.003	2.977	5.194	8.831	10.5	13.477	1.503		18.28	46.59

14	3.89	0.05	0.002	0.003	0.099	6.611	0.010	0.4	0.449	1.503		0.04	0.11
		0.10	0.008	0.013	0.198	6.611	0.039	0.7	0.898	1.503		0.17	0.43
		0.15	0.018	0.030	0.298	6.611	0.088	1.1	1.348	1.503		0.38	0.96
		0.20	0.031	0.053	0.397	6.611	0.157	1.4	1.797	1.503		0.67	1.71
		0.25	0.049	0.083	0.496	6.611	0.245	1.8	2.246	1.503		1.05	2.67
		0.30	0.071	0.120	0.595	6.611	0.353	2.1	2.695	1.503		1.51	3.84
		0.35	0.096	0.163	0.695	6.611	0.481	2.5	3.145	1.503		2.05	5.23
		0.40	0.126	0.214	0.794	6.611	0.628	2.8	3.594	1.503		2.68	6.83
		0.45	0.159	0.270	0.893	6.611	0.795	3.2	4.043	1.503		3.39	8.64
		0.50	0.196	0.334	0.992	6.611	0.981	3.5	4.492	1.503		4.19	10.67
		0.55	0.237	0.404	1.092	6.611	1.187	3.9	4.942	1.503		5.07	12.91
		0.60	0.283	0.480	1.191	6.611	1.413	4.2	5.391	1.503		6.03	15.37
		0.65	0.332	0.564	1.290	6.611	1.658	4.6	5.840	1.503		7.08	18.04
		0.70	0.385	0.654	1.389	6.611	1.923	4.9	6.289	1.503		8.21	20.92
		0.75	0.442	0.751	1.489	6.611	2.208	5.3	6.739	1.503		9.42	24.01
		0.80	0.502	0.854	1.588	6.611	2.512	5.6	7.188	1.503		10.72	27.32
		0.85	0.567	0.964	1.687	6.611	2.836	6.0	7.637	1.503		12.10	30.84
		0.90	0.636	1.081	1.786	6.611	3.179	6.3	8.086	1.503		13.57	34.58
		0.95	0.708	1.204	1.886	6.611	3.542	6.7	8.536	1.503		15.12	38.53
		1.00	0.785	1.335	1.985	6.611	3.925	7.0	8.985	1.503		16.75	42.69
		1.05	0.865	1.471	2.084	6.611	4.327	7.4	9.434	1.503		18.47	47.07
		1.10	0.950	1.615	2.183	6.611	4.749	7.7	9.883	1.503		20.27	51.66
		1.15	1.038	1.765	2.283	6.611	5.191	8.1	10.333	1.503		22.16	56.46
		1.20	1.130	1.922	2.382	6.611	5.652	8.4	10.782	1.503		24.12	61.47
		1.25	1.227	2.085	2.481	6.611	6.133	8.8	11.231	1.503		26.18	66.70
		1.30	1.327	2.255	2.580	6.611	6.633	9.1	11.680	1.503		28.31	72.15
		1.35	1.431	2.432	2.680	6.611	7.153	9.5	12.130	1.503		30.53	77.80
		1.40	1.539	2.616	2.779	6.611	7.693	9.8	12.579	1.503		32.84	83.67
		1.45	1.650	2.806	2.878	6.611	8.252	10.2	13.028	1.503		35.22	89.76
		1.50	1.766	3.003	2.977	6.611	8.831	10.5	13.477	1.503		37.69	96.05
17	4.72	0.05	0.002	0.003	0.099	8.028	0.010	0.4	0.449	1.503		0.07	0.19
		0.10	0.008	0.013	0.198	8.028	0.039	0.7	0.898	1.503		0.30	0.76
		0.15	0.018	0.030	0.298	8.028	0.088	1.1	1.348	1.503		0.67	1.72
		0.20	0.031	0.053	0.397	8.028	0.157	1.4	1.797	1.503		1.20	3.06
		0.25	0.049	0.083	0.496	8.028	0.245	1.8	2.246	1.503		1.87	4.78
		0.30	0.071	0.120	0.595	8.028	0.353	2.1	2.695	1.503		2.70	6.88
		0.35	0.096	0.163	0.695	8.028	0.481	2.5	3.145	1.503		3.67	9.36
		0.40	0.126	0.214	0.794	8.028	0.628	2.8	3.594	1.503		4.80	12.23
		0.45	0.159	0.270	0.893	8.028	0.795	3.2	4.043	1.503		6.07	15.48
		0.50	0.196	0.334	0.992	8.028	0.981	3.5	4.492	1.503		7.50	19.11
		0.55	0.237	0.404	1.092	8.028	1.187	3.9	4.942	1.503		9.07	23.12
		0.60	0.283	0.480	1.191	8.028	1.413	4.2	5.391	1.503		10.80	27.52
		0.65	0.332	0.564	1.290	8.028	1.658	4.6	5.840	1.503		12.67	32.29
		0.70	0.385	0.654	1.389	8.028	1.923	4.9	6.289	1.503		14.70	37.45
		0.75	0.442	0.751	1.489	8.028	2.208	5.3	6.739	1.503		16.87	42.99
		0.80	0.502	0.854	1.588	8.028	2.512	5.6	7.188	1.503		19.20	48.92
		0.85	0.567	0.964	1.687	8.028	2.836	6.0	7.637	1.503		21.67	55.22
		0.90	0.636	1.081	1.786	8.028	3.179	6.3	8.086	1.503		24.30	61.91
		0.95	0.708	1.204	1.886	8.028	3.542	6.7	8.536	1.503		27.07	68.98
		1.00	0.785	1.335	1.985	8.028	3.925	7.0	8.985	1.503		29.99	76.43
		1.05	0.865	1.471	2.084	8.028	4.327	7.4	9.434	1.503		33.07	84.27
		1.10	0.950	1.615	2.183	8.028	4.749	7.7	9.883	1.503		36.29	92.49
		1.15	1.038	1.765	2.283	8.028	5.191	8.1	10.333	1.503		39.67	101.09
		1.20	1.130	1.922	2.382	8.028	5.652	8.4	10.782	1.503		43.19	110.07
		1.25	1.227	2.085	2.481	8.028	6.133	8.8	11.231	1.503		46.87	119.43
		1.30	1.327	2.255	2.580	8.028	6.633	9.1	11.680	1.503		50.69	129.18
		1.35	1.431	2.432	2.680	8.028	7.153	9.5	12.130	1.503		54.67	139.30
		1.40	1.539	2.616	2.779	8.028	7.693	9.8	12.579	1.503		58.79	149.81
		1.45	1.650	2.806	2.878	8.028	8.252	10.2	13.028	1.503		63.06	160.70
		1.50	1.766	3.003	2.977	8.028	8.831	10.5	13.477	1.503		67.49	171.98
20	5.56	0.05	0.002	0.003	0.099	9.445	0.010	0.4	0.449	1.503		0.12	0.31
		0.10	0.008	0.013	0.198	9.445	0.039	0.7	0.898	1.503		0.49	1.24
		0.15	0.018	0.030	0.298	9.445	0.088	1.1	1.348	1.503		1.10	2.80
		0.20	0.031	0.053	0.397	9.445	0.157	1.4	1.797	1.503		1.95	4.98
		0.25	0.049	0.083	0.496	9.445	0.245	1.8	2.246	1.503		3.05	7.78
		0.30	0.071	0.120	0.595	9.445	0.353	2.1	2.695	1.503		4.40	11.20
		0.35	0.096	0.163	0.695	9.445	0.481	2.5	3.145	1.503		5.98	15.25
		0.40	0.126	0.214	0.794	9.445	0.628	2.8	3.594	1.503		7.81	19.91
		0.45	0.159	0.270	0.893	9.445	0.795	3.2	4.043	1.503		9.89	25.20
		0.50	0.196	0.334	0.992	9.445	0.981	3.5	4.492	1.503		12.21	31.12
		0.55	0.237	0.404	1.092	9.445	1.187	3.9	4.942	1.503		14.77	37.65
		0.60	0.283	0.480	1.191	9.445	1.413	4.2	5.391	1.503		17.58	44.81
		0.65	0.332	0.564	1.290	9.445	1.658	4.6	5.840	1.503		20.64	52.59
		0.70	0.385	0.654	1.389	9.445	1.923	4.9	6.289	1.503		23.93	60.99
		0.75	0.442	0.751	1.489	9.445	2.208	5.3	6.739	1.503		27.47	70.01
		0.80	0.502	0.854	1.588	9.445	2.512	5.6	7.188	1.503		31.26	79.66
		0.85	0.567	0.964	1.687	9.445	2.836	6.0	7.637	1.503		35.29	89.92
		0.90	0.636	1.081	1.786	9.445	3.179	6.3	8.086	1.503		39.56	100.81
		0.95	0.708	1.204	1.886	9.445	3.542	6.7	8.536	1.503		44.08	112.33
		1.00	0.785	1.335	1.985	9.445	3.925	7.0	8.985	1.503		48.84	124.46
		1.05	0.865	1.471	2.084	9.445	4.327	7.4	9.434	1.503		53.85	137.22
		1.10	0.950	1.615	2.183	9.445	4.749	7.7	9.883	1.503		59.10	150.60
		1.15	1.038	1.765	2.283	9.445	5.191	8.1	10.333	1.503		64.59	164.60
		1.20	1.130	1.922	2.382	9.445	5.652	8.4	10.782	1.503		70.33	179.22
		1.25	1.227	2.085	2.481	9.445	6.133	8.8	11.231	1.503		76.31	194.47
		1.30	1.327	2.255	2.580	9.445	6.633	9.1	11.680	1.503		82.54	210.34
		1.35	1.431	2.432	2.680	9.445	7.153	9.5	12.130	1.503		89.01	226.83
		1.40	1.539	2.616	2.779	9.445	7.693	9.8	12.579	1.503		95.73	243.94
		1.45	1.650	2.806	2.878	9.445	8.252	10.2	13.028	1.503		102.69	261.68
		1.50	1.766	3.003	2.977	9.445	8.831	10.5	13.477	1.503		109.89	280.04

23	6.39	0.05	0.002	0.003	0.099	10.861	0.010	0.4	0.449	1.503		0.19	0.47
		0.10	0.008	0.013	0.198	10.861	0.039	0.7	0.898	1.503		0.74	1.89
		0.15	0.018	0.030	0.298	10.861	0.088	1.1	1.348	1.503		1.67	4.26
		0.20	0.031	0.053	0.397	10.861	0.157	1.4	1.797	1.503		2.97	7.57
		0.25	0.049	0.083	0.496	10.861	0.245	1.8	2.246	1.503		4.64	11.83
		0.30	0.071	0.120	0.595	10.861	0.353	2.1	2.695	1.503		6.69	17.04
		0.35	0.096	0.163	0.695	10.861	0.481	2.5	3.145	1.503		9.10	23.19
		0.40	0.126	0.214	0.794	10.861	0.628	2.8	3.594	1.503		11.89	30.29
		0.45	0.159	0.270	0.893	10.861	0.795	3.2	4.043	1.503		15.04	38.33
		0.50	0.196	0.334	0.992	10.861	0.981	3.5	4.492	1.503		18.57	47.32
		0.55	0.237	0.404	1.092	10.861	1.187	3.9	4.942	1.503		22.47	57.26
		0.60	0.283	0.480	1.191	10.861	1.413	4.2	5.391	1.503		26.74	68.14
		0.65	0.332	0.564	1.290	10.861	1.658	4.6	5.840	1.503		31.38	79.98
		0.70	0.385	0.654	1.389	10.861	1.923	4.9	6.289	1.503		36.40	92.75
		0.75	0.442	0.751	1.489	10.861	2.208	5.3	6.739	1.503		41.78	106.48
		0.80	0.502	0.854	1.588	10.861	2.512	5.6	7.188	1.503		47.54	121.15
		0.85	0.567	0.964	1.687	10.861	2.836	6.0	7.637	1.503		53.67	136.76
		0.90	0.636	1.081	1.786	10.861	3.179	6.3	8.086	1.503		60.17	153.33
		0.95	0.708	1.204	1.886	10.861	3.542	6.7	8.536	1.503		67.04	170.83
		1.00	0.785	1.335	1.985	10.861	3.925	7.0	8.985	1.503		74.28	189.29
		1.05	0.865	1.471	2.084	10.861	4.327	7.4	9.434	1.503		81.90	208.69
		1.10	0.950	1.615	2.183	10.861	4.749	7.7	9.883	1.503		89.88	229.04
		1.15	1.038	1.765	2.283	10.861	5.191	8.1	10.333	1.503		98.24	250.34
		1.20	1.130	1.922	2.382	10.861	5.652	8.4	10.782	1.503		106.97	272.58
		1.25	1.227	2.085	2.481	10.861	6.133	8.8	11.231	1.503		116.07	295.77
		1.30	1.327	2.255	2.580	10.861	6.633	9.1	11.680	1.503		125.54	319.90
		1.35	1.431	2.432	2.680	10.861	7.153	9.5	12.130	1.503		135.38	344.98
		1.40	1.539	2.616	2.779	10.861	7.693	9.8	12.579	1.503		145.59	371.01
		1.45	1.650	2.806	2.878	10.861	8.252	10.2	13.028	1.503		156.18	397.98
		1.50	1.766	3.003	2.977	10.861	8.831	10.5	13.477	1.503		167.13	425.90
26	7.22	0.05	0.002	0.003	0.099	12.278	0.010	0.4	0.449	1.503		0.27	0.68
		0.10	0.008	0.013	0.198	12.278	0.039	0.7	0.898	1.503		1.07	2.73
		0.15	0.018	0.030	0.298	12.278	0.088	1.1	1.348	1.503		2.41	6.15
		0.20	0.031	0.053	0.397	12.278	0.157	1.4	1.797	1.503		4.29	10.94
		0.25	0.049	0.083	0.496	12.278	0.245	1.8	2.246	1.503		6.71	17.09
		0.30	0.071	0.120	0.595	12.278	0.353	2.1	2.695	1.503		9.66	24.61
		0.35	0.096	0.163	0.695	12.278	0.481	2.5	3.145	1.503		13.14	33.50
		0.40	0.126	0.214	0.794	12.278	0.628	2.8	3.594	1.503		17.17	43.75
		0.45	0.159	0.270	0.893	12.278	0.795	3.2	4.043	1.503		21.73	55.37
		0.50	0.196	0.334	0.992	12.278	0.981	3.5	4.492	1.503		26.83	68.36
		0.55	0.237	0.404	1.092	12.278	1.187	3.9	4.942	1.503		32.46	82.72
		0.60	0.283	0.480	1.191	12.278	1.413	4.2	5.391	1.503		38.63	98.44
		0.65	0.332	0.564	1.290	12.278	1.658	4.6	5.840	1.503		45.34	115.53
		0.70	0.385	0.654	1.389	12.278	1.923	4.9	6.289	1.503		52.58	133.99
		0.75	0.442	0.751	1.489	12.278	2.208	5.3	6.739	1.503		60.36	153.81
		0.80	0.502	0.854	1.588	12.278	2.512	5.6	7.188	1.503		68.68	175.00
		0.85	0.567	0.964	1.687	12.278	2.836	6.0	7.637	1.503		77.53	197.56
		0.90	0.636	1.081	1.786	12.278	3.179	6.3	8.086	1.503		86.92	221.49
		0.95	0.708	1.204	1.886	12.278	3.542	6.7	8.536	1.503		96.84	246.78
		1.00	0.785	1.335	1.985	12.278	3.925	7.0	8.985	1.503		107.30	273.44
		1.05	0.865	1.471	2.084	12.278	4.327	7.4	9.434	1.503		118.30	301.47
		1.10	0.950	1.615	2.183	12.278	4.749	7.7	9.883	1.503		129.84	330.86
		1.15	1.038	1.765	2.283	12.278	5.191	8.1	10.333	1.503		141.91	361.63
		1.20	1.130	1.922	2.382	12.278	5.652	8.4	10.782	1.503		154.52	393.76
		1.25	1.227	2.085	2.481	12.278	6.133	8.8	11.231	1.503		167.66	427.25
		1.30	1.327	2.255	2.580	12.278	6.633	9.1	11.680	1.503		181.35	462.12
		1.35	1.431	2.432	2.680	12.278	7.153	9.5	12.130	1.503		195.56	498.35
		1.40	1.539	2.616	2.779	12.278	7.693	9.8	12.579	1.503		210.32	535.95
		1.45	1.650	2.806	2.878	12.278	8.252	10.2	13.028	1.503		225.61	574.91
		1.50	1.766	3.003	2.977	12.278	8.831	10.5	13.477	1.503		241.44	615.24
29	8.06	0.05	0.002	0.003	0.099	13.695	0.010	0.4	0.449	1.503		0.37	0.95
		0.10	0.008	0.013	0.198	13.695	0.039	0.7	0.898	1.503		1.49	3.79
		0.15	0.018	0.030	0.298	13.695	0.088	1.1	1.348	1.503		3.35	8.54
		0.20	0.031	0.053	0.397	13.695	0.157	1.4	1.797	1.503		5.96	15.18
		0.25	0.049	0.083	0.496	13.695	0.245	1.8	2.246	1.503		9.31	23.71
		0.30	0.071	0.120	0.595	13.695	0.353	2.1	2.695	1.503		13.40	34.15
		0.35	0.096	0.163	0.695	13.695	0.481	2.5	3.145	1.503		18.24	46.48
		0.40	0.126	0.214	0.794	13.695	0.628	2.8	3.594	1.503		23.82	60.71
		0.45	0.159	0.270	0.893	13.695	0.795	3.2	4.043	1.503		30.15	76.84
		0.50	0.196	0.334	0.992	13.695	0.981	3.5	4.492	1.503		37.22	94.86
		0.55	0.237	0.404	1.092	13.695	1.187	3.9	4.942	1.503		45.04	114.78
		0.60	0.283	0.480	1.191	13.695	1.413	4.2	5.391	1.503		53.60	136.60
		0.65	0.332	0.564	1.290	13.695	1.658	4.6	5.840	1.503		62.91	160.31
		0.70	0.385	0.654	1.389	13.695	1.923	4.9	6.289	1.503		72.96	185.92
		0.75	0.442	0.751	1.489	13.695	2.208	5.3	6.739	1.503		83.76	213.43
		0.80	0.502	0.854	1.588	13.695	2.512	5.6	7.188	1.503		95.30	242.84
		0.85	0.567	0.964	1.687	13.695	2.836	6.0	7.637	1.503		107.58	274.14
		0.90	0.636	1.081	1.786	13.695	3.179	6.3	8.086	1.503		120.61	307.34
		0.95	0.708	1.204	1.886	13.695	3.542	6.7	8.536	1.503		134.38	342.44
		1.00	0.785	1.335	1.985	13.695	3.925	7.0	8.985	1.503		148.90	379.44
		1.05	0.865	1.471	2.084	13.695	4.327	7.4	9.434	1.503		164.16	418.33
		1.10	0.950	1.615	2.183	13.695	4.749	7.7	9.883	1.503		180.17	459.12
		1.15	1.038	1.765	2.283	13.695	5.191	8.1	10.333	1.503		196.92	501.81
		1.20	1.130	1.922	2.382	13.695	5.652	8.4	10.782	1.503		214.42	546.39
		1.25	1.227	2.085	2.481	13.695	6.133	8.8	11.231	1.503		232.66	592.87
		1.30	1.327	2.255	2.580	13.695	6.633	9.1	11.680	1.503		251.64	641.25
		1.35	1.431	2.432	2.680	13.695	7.153	9.5	12.130	1.503		271.37	691.52
		1.40	1.539	2.616	2.779	13.695	7.693	9.8	12.579	1.503		291.84	743.70
		1.45	1.650	2.806	2.878	13.695	8.252	10.2	13.028	1.503		313.06	797.77
		1.50	1.766	3.003	2.977	13.695	8.831	10.5	13.477	1.503		335.02	853.73

32	8.89	0.05	0.002	0.003	0.099	15.111	0.010	0.4	0.449	1.503		0.50	1.27
		0.10	0.008	0.013	0.198	15.111	0.039	0.7	0.898	1.503		2.00	5.10
		0.15	0.018	0.030	0.298	15.111	0.088	1.1	1.348	1.503		4.50	11.47
		0.20	0.031	0.053	0.397	15.111	0.157	1.4	1.797	1.503		8.00	20.39
		0.25	0.049	0.083	0.496	15.111	0.245	1.8	2.246	1.503		12.50	31.86
		0.30	0.071	0.120	0.595	15.111	0.353	2.1	2.695	1.503		18.00	45.88
		0.35	0.096	0.163	0.695	15.111	0.481	2.5	3.145	1.503		24.51	62.45
		0.40	0.126	0.214	0.794	15.111	0.628	2.8	3.594	1.503		32.01	81.57
		0.45	0.159	0.270	0.893	15.111	0.795	3.2	4.043	1.503		40.51	103.23
		0.50	0.196	0.334	0.992	15.111	0.981	3.5	4.492	1.503		50.01	127.45
		0.55	0.237	0.404	1.092	15.111	1.187	3.9	4.942	1.503		60.52	154.21
		0.60	0.283	0.480	1.191	15.111	1.413	4.2	5.391	1.503		72.02	183.53
		0.65	0.332	0.564	1.290	15.111	1.658	4.6	5.840	1.503		84.52	215.39
		0.70	0.385	0.654	1.389	15.111	1.923	4.9	6.289	1.503		98.03	249.80
		0.75	0.442	0.751	1.489	15.111	2.208	5.3	6.739	1.503		112.53	286.76
		0.80	0.502	0.854	1.588	15.111	2.512	5.6	7.188	1.503		128.04	326.27
		0.85	0.567	0.964	1.687	15.111	2.836	6.0	7.637	1.503		144.54	368.33
		0.90	0.636	1.081	1.786	15.111	3.179	6.3	8.086	1.503		162.04	412.93
		0.95	0.708	1.204	1.886	15.111	3.542	6.7	8.536	1.503		180.55	460.09
		1.00	0.785	1.335	1.985	15.111	3.925	7.0	8.985	1.503		200.06	509.79
		1.05	0.865	1.471	2.084	15.111	4.327	7.4	9.434	1.503		220.56	562.05
		1.10	0.950	1.615	2.183	15.111	4.749	7.7	9.883	1.503		242.07	616.85
		1.15	1.038	1.765	2.283	15.111	5.191	8.1	10.333	1.503		264.57	674.20
		1.20	1.130	1.922	2.382	15.111	5.652	8.4	10.782	1.503		288.08	734.10
		1.25	1.227	2.085	2.481	15.111	6.133	8.8	11.231	1.503		312.59	796.55
		1.30	1.327	2.255	2.580	15.111	6.633	9.1	11.680	1.503		338.09	861.55
		1.35	1.431	2.432	2.680	15.111	7.153	9.5	12.130	1.503		364.60	929.10
		1.40	1.539	2.616	2.779	15.111	7.693	9.8	12.579	1.503		392.11	999.20
		1.45	1.650	2.806	2.878	15.111	8.252	10.2	13.028	1.503		420.62	1071.84
		1.50	1.766	3.003	2.977	15.111	8.831	10.5	13.477	1.503		450.12	1147.04
35	9.72	0.05	0.002	0.003	0.099	16.528	0.010	0.4	0.449	1.503		0.65	1.67
		0.10	0.008	0.013	0.198	16.528	0.039	0.7	0.898	1.503		2.62	6.67
		0.15	0.018	0.030	0.298	16.528	0.088	1.1	1.348	1.503		5.89	15.01
		0.20	0.031	0.053	0.397	16.528	0.157	1.4	1.797	1.503		10.47	26.68
		0.25	0.049	0.083	0.496	16.528	0.245	1.8	2.246	1.503		16.36	41.69
		0.30	0.071	0.120	0.595	16.528	0.353	2.1	2.695	1.503		23.56	60.03
		0.35	0.096	0.163	0.695	16.528	0.481	2.5	3.145	1.503		32.07	81.71
		0.40	0.126	0.214	0.794	16.528	0.628	2.8	3.594	1.503		41.88	106.73
		0.45	0.159	0.270	0.893	16.528	0.795	3.2	4.043	1.503		53.01	135.07
		0.50	0.196	0.334	0.992	16.528	0.981	3.5	4.492	1.503		65.44	166.76
		0.55	0.237	0.404	1.092	16.528	1.187	3.9	4.942	1.503		79.18	201.78
		0.60	0.283	0.480	1.191	16.528	1.413	4.2	5.391	1.503		94.23	240.13
		0.65	0.332	0.564	1.290	16.528	1.658	4.6	5.840	1.503		110.59	281.82
		0.70	0.385	0.654	1.389	16.528	1.923	4.9	6.289	1.503		128.26	326.85
		0.75	0.442	0.751	1.489	16.528	2.208	5.3	6.739	1.503		147.24	375.21
		0.80	0.502	0.854	1.588	16.528	2.512	5.6	7.188	1.503		167.53	426.90
		0.85	0.567	0.964	1.687	16.528	2.836	6.0	7.637	1.503		189.12	481.93
		0.90	0.636	1.081	1.786	16.528	3.179	6.3	8.086	1.503		212.03	540.30
		0.95	0.708	1.204	1.886	16.528	3.542	6.7	8.536	1.503		236.24	602.00
		1.00	0.785	1.335	1.985	16.528	3.925	7.0	8.985	1.503		261.76	667.04
		1.05	0.865	1.471	2.084	16.528	4.327	7.4	9.434	1.503		288.59	735.41
		1.10	0.950	1.615	2.183	16.528	4.749	7.7	9.883	1.503		316.73	807.11
		1.15	1.038	1.765	2.283	16.528	5.191	8.1	10.333	1.503		346.18	882.16
		1.20	1.130	1.922	2.382	16.528	5.652	8.4	10.782	1.503		376.93	960.53
		1.25	1.227	2.085	2.481	16.528	6.133	8.8	11.231	1.503		409.00	1042.24
		1.30	1.327	2.255	2.580	16.528	6.633	9.1	11.680	1.503		442.37	1127.29
		1.35	1.431	2.432	2.680	16.528	7.153	9.5	12.130	1.503		477.06	1215.67
		1.40	1.539	2.616	2.779	16.528	7.693	9.8	12.579	1.503		513.05	1307.39
		1.45	1.650	2.806	2.878	16.528	8.252	10.2	13.028	1.503		550.35	1402.44
		1.50	1.766	3.003	2.977	16.528	8.831	10.5	13.477	1.503		588.96	1500.83
38	10.56	0.05	0.002	0.003	0.099	17.945	0.010	0.4	0.449	1.503		0.84	2.13
		0.10	0.008	0.013	0.198	17.945	0.039	0.7	0.898	1.503		3.35	8.54
		0.15	0.018	0.030	0.298	17.945	0.088	1.1	1.348	1.503		7.54	19.21
		0.20	0.031	0.053	0.397	17.945	0.157	1.4	1.797	1.503		13.40	34.15
		0.25	0.049	0.083	0.496	17.945	0.245	1.8	2.246	1.503		20.94	53.36
		0.30	0.071	0.120	0.595	17.945	0.353	2.1	2.695	1.503		30.15	76.83
		0.35	0.096	0.163	0.695	17.945	0.481	2.5	3.145	1.503		41.04	104.58
		0.40	0.126	0.214	0.794	17.945	0.628	2.8	3.594	1.503		53.60	136.59
		0.45	0.159	0.270	0.893	17.945	0.795	3.2	4.043	1.503		67.84	172.87
		0.50	0.196	0.334	0.992	17.945	0.981	3.5	4.492	1.503		83.75	213.42
		0.55	0.237	0.404	1.092	17.945	1.187	3.9	4.942	1.503		101.34	258.24
		0.60	0.283	0.480	1.191	17.945	1.413	4.2	5.391	1.503		120.60	307.33
		0.65	0.332	0.564	1.290	17.945	1.658	4.6	5.840	1.503		141.54	360.68
		0.70	0.385	0.654	1.389	17.945	1.923	4.9	6.289	1.503		164.15	418.30
		0.75	0.442	0.751	1.489	17.945	2.208	5.3	6.739	1.503		188.44	480.20
		0.80	0.502	0.854	1.588	17.945	2.512	5.6	7.188	1.503		214.40	546.36
		0.85	0.567	0.964	1.687	17.945	2.836	6.0	7.637	1.503		242.04	616.79
		0.90	0.636	1.081	1.786	17.945	3.179	6.3	8.086	1.503		271.35	691.48
		0.95	0.708	1.204	1.886	17.945	3.542	6.7	8.536	1.503		302.34	770.45
		1.00	0.785	1.335	1.985	17.945	3.925	7.0	8.985	1.503		335.00	853.68
		1.05	0.865	1.471	2.084	17.945	4.327	7.4	9.434	1.503		369.34	941.18
		1.10	0.950	1.615	2.183	17.945	4.749	7.7	9.883	1.503		405.36	1032.96
		1.15	1.038	1.765	2.283	17.945	5.191	8.1	10.333	1.503		443.04	1128.99
		1.20	1.130	1.922	2.382	17.945	5.652	8.4	10.782	1.503		482.41	1229.30
		1.25	1.227	2.085	2.481	17.945	6.133	8.8	11.231	1.503		523.44	1333.88
		1.30	1.327	2.255	2.580	17.945	6.633	9.1	11.680	1.503		566.16	1442.72
		1.35	1.431	2.432	2.680	17.945	7.153	9.5	12.130	1.503		610.55	1555.84
		1.40	1.539	2.616	2.779	17.945	7.693	9.8	12.579	1.503		656.61	1673.22
		1.45	1.650	2.806	2.878	17.945	8.252	10.2	13.028	1.503		704.35	1794.87
		1.50	1.766	3.003	2.977	17.945	8.831	10.5	13.477	1.503		753.76	1920.78

		0.10	0.008	0.013	0.198	19.361	0.039	0.7	0.898	1.503		4.21	10.72
		0.15	0.018	0.030	0.298	19.361	0.088	1.1	1.348	1.503		9.47	24.13
		0.20	0.031	0.053	0.397	19.361	0.157	1.4	1.797	1.503		16.83	42.89
		0.25	0.049	0.083	0.496	19.361	0.245	1.8	2.246	1.503		26.30	67.02
		0.30	0.071	0.120	0.595	19.361	0.353	2.1	2.695	1.503		37.87	96.50
		0.35	0.096	0.163	0.695	19.361	0.481	2.5	3.145	1.503		51.55	131.35
		0.40	0.126	0.214	0.794	19.361	0.628	2.8	3.594	1.503		67.32	171.56
		0.45	0.159	0.270	0.893	19.361	0.795	3.2	4.043	1.503		85.21	217.13
		0.50	0.196	0.334	0.992	19.361	0.981	3.5	4.492	1.503		105.19	268.06
		0.55	0.237	0.404	1.092	19.361	1.187	3.9	4.942	1.503		127.28	324.36
		0.60	0.283	0.480	1.191	19.361	1.413	4.2	5.391	1.503		151.48	386.01
		0.65	0.332	0.564	1.290	19.361	1.658	4.6	5.840	1.503		177.78	453.03
		0.70	0.385	0.654	1.389	19.361	1.923	4.9	6.289	1.503		206.18	525.40
		0.75	0.442	0.751	1.489	19.361	2.208	5.3	6.739	1.503		236.69	603.14
		0.80	0.502	0.854	1.588	19.361	2.512	5.6	7.188	1.503		269.30	686.24
		0.85	0.567	0.964	1.687	19.361	2.836	6.0	7.637	1.503		304.01	774.70
		0.90	0.636	1.081	1.786	19.361	3.179	6.3	8.086	1.503		340.83	868.52
		0.95	0.708	1.204	1.886	19.361	3.542	6.7	8.536	1.503		379.75	967.71
		1.00	0.785	1.335	1.985	19.361	3.925	7.0	8.985	1.503		420.78	1072.25
		1.05	0.865	1.471	2.084	19.361	4.327	7.4	9.434	1.503		463.91	1182.16
		1.10	0.950	1.615	2.183	19.361	4.749	7.7	9.883	1.503		509.14	1297.43
		1.15	1.038	1.765	2.283	19.361	5.191	8.1	10.333	1.503		556.48	1418.05
		1.20	1.130	1.922	2.382	19.361	5.652	8.4	10.782	1.503		605.92	1544.04
		1.25	1.227	2.085	2.481	19.361	6.133	8.8	11.231	1.503		657.46	1675.39
		1.30	1.327	2.255	2.580	19.361	6.633	9.1	11.680	1.503		711.11	1812.11
		1.35	1.431	2.432	2.680	19.361	7.153	9.5	12.130	1.503		766.86	1954.18
		1.40	1.539	2.616	2.779	19.361	7.693	9.8	12.579	1.503		824.72	2101.61
		1.45	1.650	2.806	2.878	19.361	8.252	10.2	13.028	1.503		884.68	2254.41
		1.50	1.766	3.003	2.977	19.361	8.831	10.5	13.477	1.503		946.75	2412.57
44	12.22	0.05	0.002	0.003	0.099	20.778	0.010	0.4	0.449	1.50348		1.30	3.31
		0.10	0.008	0.013	0.198	20.778	0.039	0.7	0.898	1.50348		5.20	13.25
		0.15	0.018	0.030	0.298	20.778	0.088	1.1	1.348	1.50348		11.70	29.82
		0.20	0.031	0.053	0.397	20.778	0.157	1.4	1.797	1.50348		20.80	53.01
		0.25	0.049	0.083	0.496	20.778	0.245	1.8	2.246	1.50348		32.50	82.83
		0.30	0.071	0.120	0.595	20.778	0.353	2.1	2.695	1.50348		46.81	119.27
		0.35	0.096	0.163	0.695	20.778	0.481	2.5	3.145	1.50348		63.71	162.35
		0.40	0.126	0.214	0.794	20.778	0.628	2.8	3.594	1.50348		83.21	212.04
		0.45	0.159	0.270	0.893	20.778	0.795	3.2	4.043	1.50348		105.31	268.37
		0.50	0.196	0.334	0.992	20.778	0.981	3.5	4.492	1.50348		130.02	331.32
		0.55	0.237	0.404	1.092	20.778	1.187	3.9	4.942	1.50348		157.32	400.89
		0.60	0.283	0.480	1.191	20.778	1.413	4.2	5.391	1.50348		187.22	477.10
		0.65	0.332	0.564	1.290	20.778	1.658	4.6	5.840	1.50348		219.73	559.93
		0.70	0.385	0.654	1.389	20.778	1.923	4.9	6.289	1.50348		254.83	649.38
		0.75	0.442	0.751	1.489	20.778	2.208	5.3	6.739	1.50348		292.54	745.46
		0.80	0.502	0.854	1.588	20.778	2.512	5.6	7.188	1.50348		332.84	848.17
		0.85	0.567	0.964	1.687	20.778	2.836	6.0	7.637	1.50348		375.75	957.51
		0.90	0.636	1.081	1.786	20.778	3.179	6.3	8.086	1.50348		421.25	1073.47
		0.95	0.708	1.204	1.886	20.778	3.542	6.7	8.536	1.50348		469.36	1196.05
		1.00	0.785	1.335	1.985	20.778	3.925	7.0	8.985	1.50348		520.07	1325.27
		1.05	0.865	1.471	2.084	20.778	4.327	7.4	9.434	1.50348		573.37	1461.11
		1.10	0.950	1.615	2.183	20.778	4.749	7.7	9.883	1.50348		629.28	1603.57
		1.15	1.038	1.765	2.283	20.778	5.191	8.1	10.333	1.50348		687.79	1752.67
		1.20	1.130	1.922	2.382	20.778	5.652	8.4	10.782	1.50348		748.89	1908.38
		1.25	1.227	2.085	2.481	20.778	6.133	8.8	11.231	1.50348		812.60	2070.73
		1.30	1.327	2.255	2.580	20.778	6.633	9.1	11.680	1.50348		878.91	2239.70
		1.35	1.431	2.432	2.680	20.778	7.153	9.5	12.130	1.50348		947.82	2415.30
		1.40	1.539	2.616	2.779	20.778	7.693	9.8	12.579	1.50348		1019.33	2597.52
		1.45	1.650	2.806	2.878	20.778	8.252	10.2	13.028	1.50348		1093.44	2786.37
		1.50	1.766	3.003	2.977	20.778	8.831	10.5	13.477	1.50348		1170.15	2981.85
47	13.06	0.05	0.002	0.003	0.099	22.195	0.010	0.4	0.449	1.50348		1.58	4.04
		0.10	0.008	0.013	0.198	22.195	0.039	0.7	0.898	1.50348		6.34	16.15
		0.15	0.018	0.030	0.298	22.195	0.088	1.1	1.348	1.50348		14.26	36.34
		0.20	0.031	0.053	0.397	22.195	0.157	1.4	1.797	1.50348		25.35	64.61
		0.25	0.049	0.083	0.496	22.195	0.245	1.8	2.246	1.50348		39.62	100.95
		0.30	0.071	0.120	0.595	22.195	0.353	2.1	2.695	1.50348		57.05	145.37
		0.35	0.096	0.163	0.695	22.195	0.481	2.5	3.145	1.50348		77.65	197.87
		0.40	0.126	0.214	0.794	22.195	0.628	2.8	3.594	1.50348		101.42	258.44
		0.45	0.159	0.270	0.893	22.195	0.795	3.2	4.043	1.50348		128.36	327.09
		0.50	0.196	0.334	0.992	22.195	0.981	3.5	4.492	1.50348		158.46	403.81
		0.55	0.237	0.404	1.092	22.195	1.187	3.9	4.942	1.50348		191.74	488.61
		0.60	0.283	0.480	1.191	22.195	1.413	4.2	5.391	1.50348		228.19	581.49
		0.65	0.332	0.564	1.290	22.195	1.658	4.6	5.840	1.50348		267.81	682.44
		0.70	0.385	0.654	1.389	22.195	1.923	4.9	6.289	1.50348		310.59	791.47
		0.75	0.442	0.751	1.489	22.195	2.208	5.3	6.739	1.50348		356.55	908.58
		0.80	0.502	0.854	1.588	22.195	2.512	5.6	7.188	1.50348		405.67	1033.76
		0.85	0.567	0.964	1.687	22.195	2.836	6.0	7.637	1.50348		457.96	1167.02
		0.90	0.636	1.081	1.786	22.195	3.179	6.3	8.086	1.50348		513.43	1308.35
		0.95	0.708	1.204	1.886	22.195	3.542	6.7	8.536	1.50348		572.06	1457.76
		1.00	0.785	1.335	1.985	22.195	3.925	7.0	8.985	1.50348		633.86	1615.25
		1.05	0.865	1.471	2.084	22.195	4.327	7.4	9.434	1.50348		698.83	1780.81
		1.10	0.950	1.615	2.183	22.195	4.749	7.7	9.883	1.50348		766.97	1954.45
		1.15	1.038	1.765	2.283	22.195	5.191	8.1	10.333	1.50348		838.28	2136.16
		1.20	1.130	1.922	2.382	22.195	5.652	8.4	10.782	1.50348		912.76	2325.96
		1.25	1.227	2.085	2.481	22.195	6.133	8.8	11.231	1.50348		990.41	2523.82
		1.30	1.327	2.255	2.580	22.195	6.633	9.1	11.680	1.50348		1071.22	2729.77
		1.35	1.431	2.432	2.680	22.195	7.153	9.5	12.130	1.50348		1155.21	2943.79
		1.40	1.539	2.616	2.779	22.195	7.693	9.8	12.579	1.50348		1242.37	3165.88
		1.45	1.650	2.806	2.878	22.195	8.252	10.2	13.028	1.50348		1332.69	3396.06
		1.50	1.766	3.003	2.977	22.195	8.831	10.5	13.477	1.50348		1426.18	3634.31

50	13.89	0.05	0.002	0.003	0.099	23.611	0.010	0.4	0.449	1.50348		1.91	4.86
		0.10	0.008	0.013	0.198	23.611	0.039	0.7	0.898	1.50348		7.63	19.45
		0.15	0.018	0.030	0.298	23.611	0.088	1.1	1.348	1.50348		17.17	43.76
		0.20	0.031	0.053	0.397	23.611	0.157	1.4	1.797	1.50348		30.53	77.79
		0.25	0.049	0.083	0.496	23.611	0.245	1.8	2.246	1.50348		47.70	121.54
		0.30	0.071	0.120	0.595	23.611	0.353	2.1	2.695	1.50348		68.68	175.02
		0.35	0.096	0.163	0.695	23.611	0.481	2.5	3.145	1.50348		93.49	238.23
		0.40	0.126	0.214	0.794	23.611	0.628	2.8	3.594	1.50348		122.10	311.15
		0.45	0.159	0.270	0.893	23.611	0.795	3.2	4.043	1.50348		154.54	393.80
		0.50	0.196	0.334	0.992	23.611	0.981	3.5	4.492	1.50348		190.79	486.18
		0.55	0.237	0.404	1.092	23.611	1.187	3.9	4.942	1.50348		230.85	588.28
		0.60	0.283	0.480	1.191	23.611	1.413	4.2	5.391	1.50348		274.73	700.10
		0.65	0.332	0.564	1.290	23.611	1.658	4.6	5.840	1.50348		322.43	821.64
		0.70	0.385	0.654	1.389	23.611	1.923	4.9	6.289	1.50348		373.94	952.91
		0.75	0.442	0.751	1.489	23.611	2.208	5.3	6.739	1.50348		429.27	1093.90
		0.80	0.502	0.854	1.588	23.611	2.512	5.6	7.188	1.50348		488.42	1244.62
		0.85	0.567	0.964	1.687	23.611	2.836	6.0	7.637	1.50348		551.38	1405.05
		0.90	0.636	1.081	1.786	23.611	3.179	6.3	8.086	1.50348		618.15	1575.22
		0.95	0.708	1.204	1.886	23.611	3.542	6.7	8.536	1.50348		688.74	1755.10
		1.00	0.785	1.335	1.985	23.611	3.925	7.0	8.985	1.50348		763.15	1944.71
		1.05	0.865	1.471	2.084	23.611	4.327	7.4	9.434	1.50348		841.37	2144.05
		1.10	0.950	1.615	2.183	23.611	4.749	7.7	9.883	1.50348		923.41	2353.10
		1.15	1.038	1.765	2.283	23.611	5.191	8.1	10.333	1.50348		1009.27	2571.88
		1.20	1.130	1.922	2.382	23.611	5.652	8.4	10.782	1.50348		1098.94	2800.39
		1.25	1.227	2.085	2.481	23.611	6.133	8.8	11.231	1.50348		1192.42	3038.61
		1.30	1.327	2.255	2.580	23.611	6.633	9.1	11.680	1.50348		1289.72	3286.56
		1.35	1.431	2.432	2.680	23.611	7.153	9.5	12.130	1.50348		1390.84	3544.24
		1.40	1.539	2.616	2.779	23.611	7.693	9.8	12.579	1.50348		1495.77	3811.64
		1.45	1.650	2.806	2.878	23.611	8.252	10.2	13.028	1.50348		1604.52	4088.76
		1.50	1.766	3.003	2.977	23.611	8.831	10.5	13.477	1.50348		1717.09	4375.60
55	15.2779	0.05	0.002	0.003	0.099	25.972	0.010	0.4	0.449	1.50348		2.54	6.47
		0.10	0.008	0.013	0.198	25.972	0.039	0.7	0.898	1.50348		10.16	25.88
		0.15	0.018	0.030	0.298	25.972	0.088	1.1	1.348	1.50348		22.85	58.24
		0.20	0.031	0.053	0.397	25.972	0.157	1.4	1.797	1.50348		40.63	103.54
		0.25	0.049	0.083	0.496	25.972	0.245	1.8	2.246	1.50348		63.48	161.78
		0.30	0.071	0.120	0.595	25.972	0.353	2.1	2.695	1.50348		91.42	232.96
		0.35	0.096	0.163	0.695	25.972	0.481	2.5	3.145	1.50348		124.43	317.08
		0.40	0.126	0.214	0.794	25.972	0.628	2.8	3.594	1.50348		162.52	414.15
		0.45	0.159	0.270	0.893	25.972	0.795	3.2	4.043	1.50348		205.69	524.15
		0.50	0.196	0.334	0.992	25.972	0.981	3.5	4.492	1.50348		253.94	647.10
		0.55	0.237	0.404	1.092	25.972	1.187	3.9	4.942	1.50348		307.27	782.99
		0.60	0.283	0.480	1.191	25.972	1.413	4.2	5.391	1.50348		365.67	931.83
		0.65	0.332	0.564	1.290	25.972	1.658	4.6	5.840	1.50348		429.16	1093.60
		0.70	0.385	0.654	1.389	25.972	1.923	4.9	6.289	1.50348		497.72	1268.32
		0.75	0.442	0.751	1.489	25.972	2.208	5.3	6.739	1.50348		571.36	1455.98
		0.80	0.502	0.854	1.588	25.972	2.512	5.6	7.188	1.50348		650.08	1656.58
		0.85	0.567	0.964	1.687	25.972	2.836	6.0	7.637	1.50348		733.88	1870.13
		0.90	0.636	1.081	1.786	25.972	3.179	6.3	8.086	1.50348		822.76	2096.61
		0.95	0.708	1.204	1.886	25.972	3.542	6.7	8.536	1.50348		916.72	2336.04
		1.00	0.785	1.335	1.985	25.972	3.925	7.0	8.985	1.50348		1015.75	2588.41
		1.05	0.865	1.471	2.084	25.972	4.327	7.4	9.434	1.50348		1119.87	2853.72
		1.10	0.950	1.615	2.183	25.972	4.749	7.7	9.883	1.50348		1229.06	3131.98
		1.15	1.038	1.765	2.283	25.972	5.191	8.1	10.333	1.50348		1343.33	3423.17
		1.20	1.130	1.922	2.382	25.972	5.652	8.4	10.782	1.50348		1462.68	3727.31
		1.25	1.227	2.085	2.481	25.972	6.133	8.8	11.231	1.50348		1587.11	4044.39
		1.30	1.327	2.255	2.580	25.972	6.633	9.1	11.680	1.50348		1716.62	4374.42
		1.35	1.431	2.432	2.680	25.972	7.153	9.5	12.130	1.50348		1851.21	4717.38
		1.40	1.539	2.616	2.779	25.972	7.693	9.8	12.579	1.50348		1990.87	5073.29
		1.45	1.650	2.806	2.878	25.972	8.252	10.2	13.028	1.50348		2135.62	5442.14
		1.50	1.766	3.003	2.977	25.972	8.831	10.5	13.477	1.50348		2285.44	5823.93
60	16.6668	0.05	0.002	0.003	0.099	28.334	0.010	0.4	0.449	1.50348		3.30	8.40
		0.10	0.008	0.013	0.198	28.334	0.039	0.7	0.898	1.50348		13.19	33.60
		0.15	0.018	0.030	0.298	28.334	0.088	1.1	1.348	1.50348		29.67	75.61
		0.20	0.031	0.053	0.397	28.334	0.157	1.4	1.797	1.50348		52.75	134.42
		0.25	0.049	0.083	0.496	28.334	0.245	1.8	2.246	1.50348		82.42	210.03
		0.30	0.071	0.120	0.595	28.334	0.353	2.1	2.695	1.50348		118.69	302.44
		0.35	0.096	0.163	0.695	28.334	0.481	2.5	3.145	1.50348		161.54	411.66
		0.40	0.126	0.214	0.794	28.334	0.628	2.8	3.594	1.50348		211.00	537.67
		0.45	0.159	0.270	0.893	28.334	0.795	3.2	4.043	1.50348		267.04	680.49
		0.50	0.196	0.334	0.992	28.334	0.981	3.5	4.492	1.50348		329.68	840.12
		0.55	0.237	0.404	1.092	28.334	1.187	3.9	4.942	1.50348		398.91	1016.54
		0.60	0.283	0.480	1.191	28.334	1.413	4.2	5.391	1.50348		474.74	1209.77
		0.65	0.332	0.564	1.290	28.334	1.658	4.6	5.840	1.50348		557.16	1419.80
		0.70	0.385	0.654	1.389	28.334	1.923	4.9	6.289	1.50348		646.17	1646.63
		0.75	0.442	0.751	1.489	28.334	2.208	5.3	6.739	1.50348		741.78	1890.26
		0.80	0.502	0.854	1.588	28.334	2.512	5.6	7.188	1.50348		843.98	2150.70
		0.85	0.567	0.964	1.687	28.334	2.836	6.0	7.637	1.50348		952.78	2427.93
		0.90	0.636	1.081	1.786	28.334	3.179	6.3	8.086	1.50348		1068.17	2721.97
		0.95	0.708	1.204	1.886	28.334	3.542	6.7	8.536	1.50348		1190.15	3032.82
		1.00	0.785	1.335	1.985	28.334	3.925	7.0	8.985	1.50348		1318.72	3360.46
		1.05	0.865	1.471	2.084	28.334	4.327	7.4	9.434	1.50348		1453.89	3704.91
		1.10	0.950	1.615	2.183	28.334	4.749	7.7	9.883	1.50348		1595.65	4066.16
		1.15	1.038	1.765	2.283	28.334	5.191	8.1	10.333	1.50348		1744.01	4444.21
		1.20	1.130	1.922	2.382	28.334	5.652	8.4	10.782	1.50348		1898.96	4839.07
		1.25	1.227	2.085	2.481	28.334	6.133	8.8	11.231	1.50348		2060.50	5250.72
		1.30	1.327	2.255	2.580	28.334	6.633	9.1	11.680	1.50348		2228.64	5679.18
		1.35	1.431	2.432	2.680	28.334	7.153	9.5	12.130	1.50348		2403.37	6124.44
		1.40	1.539	2.616	2.779	28.334	7.693	9.8	12.579	1.50348		2584.70	6586.51
		1.45	1.650	2.806	2.878	28.334	8.252	10.2	13.028	1.50348		2772.61	7065.37
		1.50	1.766	3.003	2.977	28.334	8.831	10.5	13.477	1.50348		2967.13	7561.04