DIPLOMARBEIT

Urban Wind Turbines
A Literature Review on Current Research

unter der Leitung von

Univ.-Prof. DI Dr. Ardeshir Mahdavi

E 259-3 Abteilung für Building Science and Technology

Institut für Building Physics and Building Ecology

eingereicht an der

Technischen Universität Wien

Fakultät für Architektur und Raumplanung

von

Aikaterini Konstantina Chrysochou

01607337

Hermanngasse 12, 1070, Vienna

Wien, April 2021

(DEUTSCHE) KURZFASSUNG

Im Zuge der Klimakrise und sinkender Kosten ist der Bedarf und die Nutzung erneuerbarer Energien in den letzten Jahren rapide angestiegen. Einen signifikanten Beitrag zu diesem Anstieg steuern dezentrale Kleinanlagen in Siedlungsgebieten bei. Neben einer potenziellen höheren Energieeffizienz, erhöhen Kleinanlagen zudem die Energieautarkie und Resilienz. Während sich die Fotovoltaik relativ weit im Stadtbild etablieren konnte, bleiben Kleinwindanlagen als potenzielle Energieerzeuger weitgehend die Ausnahme und ihr Potenzial ungenutzt. Ziel der vorliegenden Arbeit ist es, den aktuellen Stand der Technik, den Wirkungsgrad und die Wirtschaftlichkeit von Kleinwindanlagen nachzuvollziehen. Schließlich wird anhand eines Fallbeispiels das theoretische Potenzial von urbanen Windanlagen zur Energiebedarfsabdeckung der Stadt Wien im Verhältnis ihrer Wirtschaftlichkeit untersucht. Methodisch basiert die Arbeit auf einer umfassenden Recherche der Fachliteratur, die durch vier Kategorien strukturiert analysieret wurde: Leistung und Wirkungsgrad von Kleinwindanlagen, deren bauliche Integration in die Stadt und Gebäude, Lärmemission und Wirtschaftlichkeit. Im Kapitel Diskussion stellt sich heraus, dass sich ein großer Teil der Forschung auf die Leistungserhöhung und die lokale Standort Optimierung innerhalb der Stadt und auf Gebäuden fokussiert. Signifikante Unterschiede der Performanz im Hinblick auf Standortentscheidungen, empfehlen darüber hinaus die Anwendung von numerischen Windsimulation (Computational Fluid Dynamics) in der Planungsphase. Aufgrund hoher Bebauungsdichten im städtischen Kontext und die dadurch bedingte Platzknappheit wie geringere durchschnittliche Windgeschwindigkeiten veranlassen Hersteller zu der Konstruktion von Rotoren kleinen Durchmessers. Abschließend, unterstreicht das Fallbeispiel Wien das hohe Potenzial von städtischen Kleinwindkraftanlagen für die lokale Energiebedarfsabdeckung von Großstädten (50% des Energiebedarfs Wiens könnten durch Kleinwindkraftanlagen bedient werden), allerdings nur zu hohen Kosten und einem noch nicht Wettbewerbsfähigen Preis.

(ENGLISH) ABSTRACT

There has been a growing need for renewable energy solutions in the past years, mostly renewable energy production in cities. Wind power generation inside the city and on buildings is a type of renewable energy that could help cities improve their efficiency. However, stakeholders are still hesitant to adopt this technology and prefer other renewables, such as photovoltaics. This Master Thesis will -through a literature review- explore the performance, implementation methods, requirements, and cost of small wind turbines inside the urban canopy layer. The review investigates the latest research papers in four categories; small wind turbine performance, integration of small wind turbines on buildings and cities, noise production, and investment payoff.

Moreover, a rough estimation of Vienna's potential electricity production with small wind turbines will paint a better picture of how much of the city's demand can be covered with small wind turbines. In conclusion, through the review process, it is evident that most research focuses on performance enhancement by studying the design of the turbine and the position in the city. Researchers mostly use numerical simulation tools to complete their study, which illustrates the importance of computational fluid dynamics in building efficient small wind turbines. Moreover, producers focus on turbines that start at low wind speed and have a small rotor because in cities, the average wind speed is low, and buildings cannot support oversized rotors. Lastly, results show that small wind turbines can cover up to 50% of Vienna's electricity consumption, however, it would be costly.

Overall, this contribution aims to fill the knowledge gap on the methods for wind energy in cities and buildings and show the potential of producing electricity through a discussion and suggestion for further research.

Keywords

Small Wind Turbines; Urban Conditions; Energy Performance; Building Integrated Turbines;

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis supervisor and mentor, Univ. Prof. DI Dr. Ardeshir Mahdavi, for offering me this opportunity, giving me the freedom to work independently, and for being there whenever I needed help despite his super-tight schedule. His words when I was looking for a thesis topic, "I want you to work on something that you are excited about," will always stay with me. Thanks to his Master's program, I have had the honor to meet and interact with many brilliant people from around the world and learn from them.

I would like to thank DI Magdalena Wölzl, for her excellent insights and ideas. Especially for taking the time to explain everything to me in a language that is not her native. She has been a great mentor throughout this journey.

I would also like to thank my sister DI Angeliki Chrysochou for believing in me and motivating me to do better. She leads by example, and she is the best role model I could ever have.

My parents DI Nikolaos Chrysochou and Fotini Chrysochou, have always encouraged me to pursue what I like, despite many hardships they had to face. I am eternally grateful to them and my sister for their love, education, and support, for I wouldn't be here without them.

My special thanks go to Dr. Iriana Vlachopoulou for being there for me in times of crisis, and for helping me get a glimpse of the work of the United Nations.

I would like to thank Ph.D. candidate DI Aditya Kapilavai for sharing his excitement about science with me and motivating me to work thoroughly, and DI Serjoscha Duering for helping me with German.

Lastly, I would like to thank my coworkers, especially DI Dr. Ali Hainoun and DI Dr. Martin Traunmueller, for making me part of their teams and allowing me to work on exciting research projects.

NOMENCLATURE

Abbreviation	Meaning
SWTs	Small Wind Turbines
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
AEO	Annual Energy Output
UWTs	Urban Wind turbines
Cp	Power Coefficient

CONTENTS

1 INTRODUCTION

1.1 Overview

The world's primary energy sources are degrading; the traditional ways to extract energy (i.e., coal, gas) are not only running out but also harming the environment with CO2 emissions, expediting climate change. Humankind is called to find solutions to mitigate the outcomes of that inevitable change. Plenty of renewable resources technologies are advancing to the extent that the world should entirely rely on renewables, such as solar energy or wind energy, alone in the future. Contrary to solar, the wind is an unceasing energy source; therefore, a potential solution is to harness the wind.

One of the possible ways to harness wind is through wind turbines. Wind turbine technologies can be structured in different ways, altitudes, orientation as well as material. Still, there are requirements to harvest the technology's potential, such as the wind potential of the area -and according to that- the type of wind turbine that will be used and the altitude it will be placed. Moreover, an advantageous way of harvesting wind is using small wind turbines in cities; they satisfy the immediate need for energy. Moreover, they minimize traditional wind turbines' disadvantages since they are used where consumption occurs (KC et al. 2019b).

Most cities developed in an era where protecting the Earth and adapting to severe climate phenomena were not primary concerns. Therefore, their development evolved so that -currently- cities constitute the primary source of CO2 emissions and contribute significantly to climate change (Awano n.d.). As several studies indicate, buildings being the main city element, they constitute the primary energy consumption source in the urban context (Cao et al. 2016). While a paradigm shift might be difficult to implement, alternative solutions to building energy consumption can be found in nature.

This thesis aims to explore the topic of small wind turbines in cities; the study achieves its objective through a comprehensive literature review of current research and rough estimations about electricity coverage in the city of Vienna, and a list of small wind turbine suppliers with technical specifications. Moreover, there will be a comparison between the scientific paper conclusions and findings from technical specifications.

The statistical analysis of the findings provides a holistic approach to the topic and valuable insight into the answers to the research question of why small wind turbines, though not particularly popular, are essential to shift towards a renewable future for energy consumption.

1.2 Motivation

The importance of city integrated wind turbines lies in the need for energy resources. Sustainable cities would profoundly impact living conditions globally, reducing the toll that the evolution of humankind's energy need is expected to have on our planet. Societies use vast amounts of energy to heat buildings for residential use, services, and industry (Sugahara n.d.). Constant population growth, along with economic growth, signify rapidly increasing energy demand.

Renewable resources are considered infinite, as weather phenomena, the primary sources of renewable energy, occur since the earth's existence. The sun, the wind, running water, organic sources such as wood are sources of energy that are constantly renewed. These energy sources used to be the primary means of energy production until the beginning of the 20th century and the Industrial revolution, when societies turned to utilize coal (Unger 2013).

Among the various renewable energy sources influenced by changes in Earth's atmosphere, the wind is created due to atmospheric pressure changes. In addition, changes to the wind stream occur because there are different temperatures on the earth's surface (Bichet et al. 2012). As the Earth is made of various materials with different absorbance factors, soil and water absorb heat differently and cause a temperature divergence that results in winds. Furthermore, the morphology of the ground forms various streams of wind (Ishugah et al. 2014). Considering that morphology changes the behaviour of wind, cities tend to develop their own wind patterns, not only because there are differentiations on the ground, but also because buildings create a supplementary shape to the ground's surface (Simiu and Scanlan 1996).

In order to consider an area suitable for wind turbines, wind speeds have to reach more than 4m/s (measured 10m above ground), which is the height of a standard anemometer (WMO n.d.). There are plenty of areas worldwide that fulfil that prerequisite, mostly non-residential areas, hence suitable for large wind farms. Nonetheless, large wind farms have downsides, such as aesthetics, the dangers they might convey to wildlife, noise pollution, and maintenance costs.

Large scale wind farms are located in remote areas. The cost of traveling to maintain them is high (Andrawus 2008); therefore, implementing the same technology on a small scale in an easily accessible location may reduce costs. Hence, cities' potential is eminent, and small wind turbines can harness wind inside the urban canopy layer. Consequently, there is no need to utilize vast amounts of land, and energy can be produced where it is needed, within the city's confines.

Since wind turbines are used mostly in wind farms and are not particularly popular in cities, there is a lack of concentrated resources on the new advancements that can be incorporated in an urban environment. The existence of concentrated resources is valuable because it can showcase the benefits of wind-generated energy produced by small scale wind turbines.

1.3 Background

Critics of the use of wind turbines argue that this technology is not as efficient as it should be, as the performance data are limited to studies done solely by manufacturers (Hewitt 2019). Therefore, individuals who do not see the return on investment as beneficial would not choose that energy efficiency method. However, lately, new advancements in the field, such as the O-Wind Turbine, channelled renewable energy from urban areas and won the James Dyson award in 2018 (Hamill 2018).

To better understand the need for this form of energy in buildings and cities, this chapter will explore the narrative of wind turbines. The provided information will establish the objectives for research, verify the research question of the needs and benefits of the implementation of small wind turbines, and eventually support the chosen research methods.

1.3.1 History of Wind Turbines

Since the beginning of the times, the wind has been an energy resource when ancient civilizations used the wind to instigate movement, known as a ship's sails. What started as an effortless way of wind-generated movement, through time, grew in output to become the first windmills in the 18th century, which were used to grind grain and pump water. However, Windmills experienced a decline in their use with the rise of more powerful energy production techniques such as steam engines, turbines, and oil and gas engines (Shepherd 2010).

As mentioned above, humankind has always used wind energy to facilitate daily practices. Interestingly, the first documented instant of wind usage to operate a machine can be found in Egypt in the 1st century AD; Heron's windmill, an organ powered by a wind-wheel, is documented as the first wind-milled powered device (Guarnieri 2017). More specifically, Heron's windmill consisted of a piston that pumped air through the organ's pipes and generated movement.

In the following years, windmills spread globally to be used for various daily tasks, such as grinding corn or flour and pumping water. In China and Sicily, the technology was used to pump seawater and crate salt. The first documented wind turbine invention was in Scotland by James Blyth; his invention consisted of a 33ft horizontal wind turbine of cloth-sailed installation, which supplied accumulators with energy, what is now known as batteries (Price 2005). For years there has been a misconception that the first wind turbine was founded in the U.S by Charles F. Brush; however, his invention came just a few months after Blyth's. Charles F. Brush’s structure consisted of a wheel with 17 meters and 144 blades on it and stood on an 18m tower. What was innovative about Brush's invention was that it had "brakes" for when intense winds occurred in the area. As Shepherd mentions, those breaks were:

"To provide a steady to relieve strain on the main post in extremely heavy winds, the tower had arms at the four corners carrying casters at their bottom ends which had a small clearance with a concentric rail let into the foundation." (Shepherd 2010 p.36).

Brush's invention is considered a milestone for renewable energy, as it was the first attempt to combine structure and aerodynamics with electrical technology.

The invention of Pour LaCour in Denmark is the first real attempt at a wind turbine. LaCour used the wind force of wind tunnels by creating a stream inside a cylinder. He did that by placing a four-bladed rotor at the inlet of the cylindrical tunnel, which helped drive the shaft's airflow. The blades and rotors followed the conventional design; however, their difference was that they had a low sail area ratio to the swept area (Shepherd 2010). This invention was the beginning of power plant implementation to agricultural activities and the springboard to creating the first power plants.

Nonetheless, even though the technology was fairly radical, it did not receive wide acceptance and was not used until world war II. During that time, airplanes were first put into massive use, and the rotor power was studied thoroughly, showcasing its potential as an energy generator. The first power plant construction started in 1925 and ended in 1931, producing energy until the end of the 50s. The power plant was based on Marcellus and Joseph Jacobs's designs, whose wind turbines could produce up to 3000w using a 110-V DC unit, which made them famous for being efficient and at the same time minimal maintenance (Guarnieri 2017). However, they were not the only ones to have an efficient design of a wind turbine rotor. The wind charger was equally successful and low cost, as well as the Savonius Rotor, a vertical axis wind turbine consisting of curved blades that drag and lift wind forces on their buckets. In the picture below, there is a graphical representation of the streams created between the buckets and the mechanism's functionality (Figure 1). It was a very innovative design that opened up the path to the creation of small wind turbines.

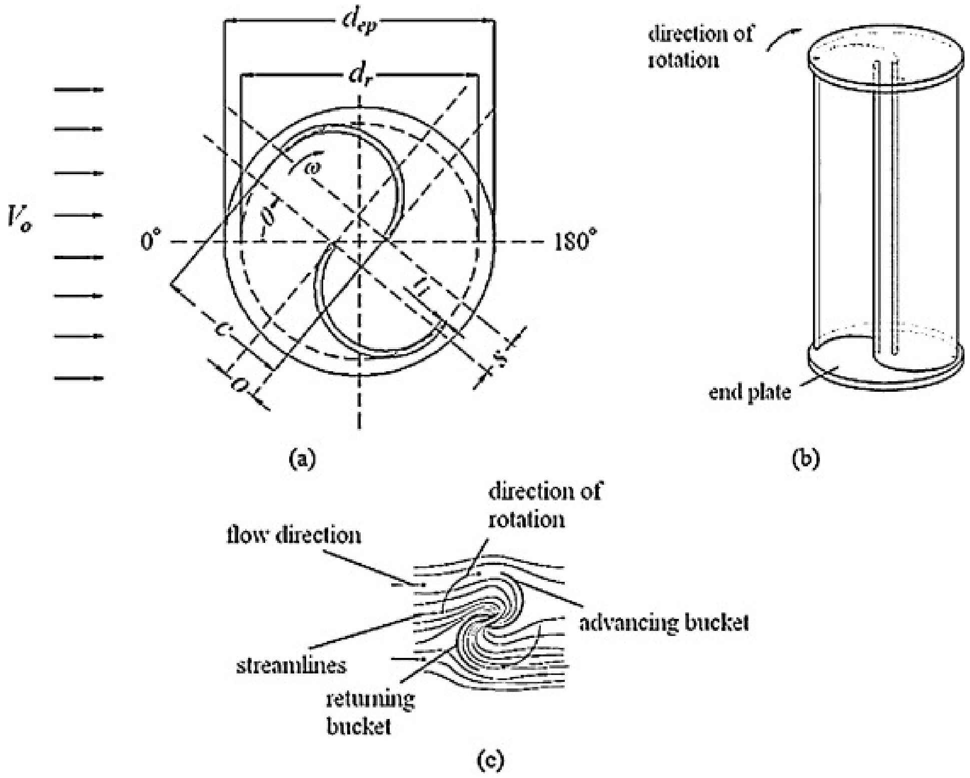


Figure 1 Design and inflow in a Savonius turbine (source: Akwa et al. 2012b)

Another innovative design that came out was the Darrieus rotor, another type of vertical wind turbine, consisting of curved blades and do not have an inner surface (Shepherd, 2010). The Darrieus rotor (Figure 2) rotates mid-axis because of the lift created by the rotating aerofoils. What distinguishes it from the Savonius rotor. The Savonius rotor moves because of the wind forces' drug (Akwa et al. 2012a), whereas the Darrieus because of the lift.

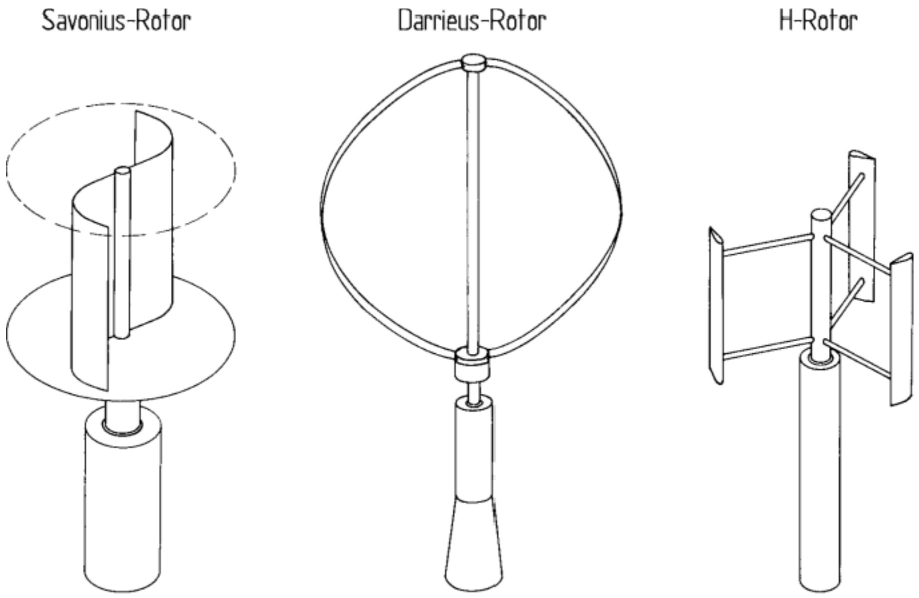


Figure 2 Types of Vertical Axis rotors (source: Saleh and Feeny 2019)

Through the years, the wind turbine generators evolved substantially, and their use became widespread. However, after World War II, with the rise of nuclear power, interest in wind power fell, and producers focused more on coal, peat, natural gas, and bioenergy, with a few exceptions in Europe (Fleming and Probert 1984).

The use and development of wind power technologies are connected to the countries' financial situation, and especially oil prices. That is why the 1973 oil crisis pushed people towards alternative power sources, particularly nuclear power. Nevertheless, public opinion had already started turning against nuclear power and its negative aspects, encouraging skeptics of nuclear powerplants to promote wind energy. Denmark, Germany, and Spain took initiatives on wind power production. In Denmark, the biggest wind turbine was commissioned in 1978, constructed by Wind Mill Team, inspiring Siemens and Vesta to develop their technologies. Simultaneously, NASA also had its fair share of funding research projects for wind power technologies until the mid-1980s and the deflation of oil prices and implementation of taxes in wind energy (Guarnieri 2017).

The evolution of wind energy shows the connection between energy consumption and demand. To better understand why there is a serious need for renewable energy in cities, one should also understand cities' energy consumption.

1.3.2 Energy Consumption in the Built Environment

Energy consumption is the amount of energy used to generate power. In the built environment, this includes not only lighting a lamp in a room but also appliances and heating and cooling. Therefore, energy consumption depends significantly on the individual use of each building and the appliances it includes.

The use of renewable energy has increased from 7,8% in 1990 to 11,5% in 2014 (OECD 2016), highlighting the need for alternative energy production methods to minimize CO_2 emissions. At the same time, a United Nations report indicates that cities' urban population is predicted to increase worldwide, with cities housing 60% of people globally and the number of cities with at least 500.000 inhabitants is expected to rise (UN 2016). According to an International Energy Agency (IEA) report in 2013, 63% of the global primary energy use was consumed by urban areas, which caused 70% of the planet's CO_2 emissions (IEA 2016).

Considering the UN report on urban population growth and the IEA report, it appears that the trend of urbanization will continue. As cities will grow, the need for energy will grow as well. As mentioned earlier, the primary source of energy consumption in cities consists of buildings. In Europe, the building stock alone is calculated to be 24 billion m^2, with most of the buildings being residential (75%) and therefore being responsible for 27% of the local consumption (Santamouris n.d.). In this regard, cities have the potential to contribute to the improvement of their overall performance.

Incorporating small wind turbines in buildings or parks and highways can increase efficiency. More specifically, by installing small wind turbines, their total cumulative capacity went from approximately 319.00 MW in 2013 to 651.000 MW in 2019 (Figure 3) (WWEA 2018). A small wind turbine can cover up to 20 KW of power and combine with other renewable energy producing utilities to bring a building to zero energy consumption (Pitteloud et al. 2017).

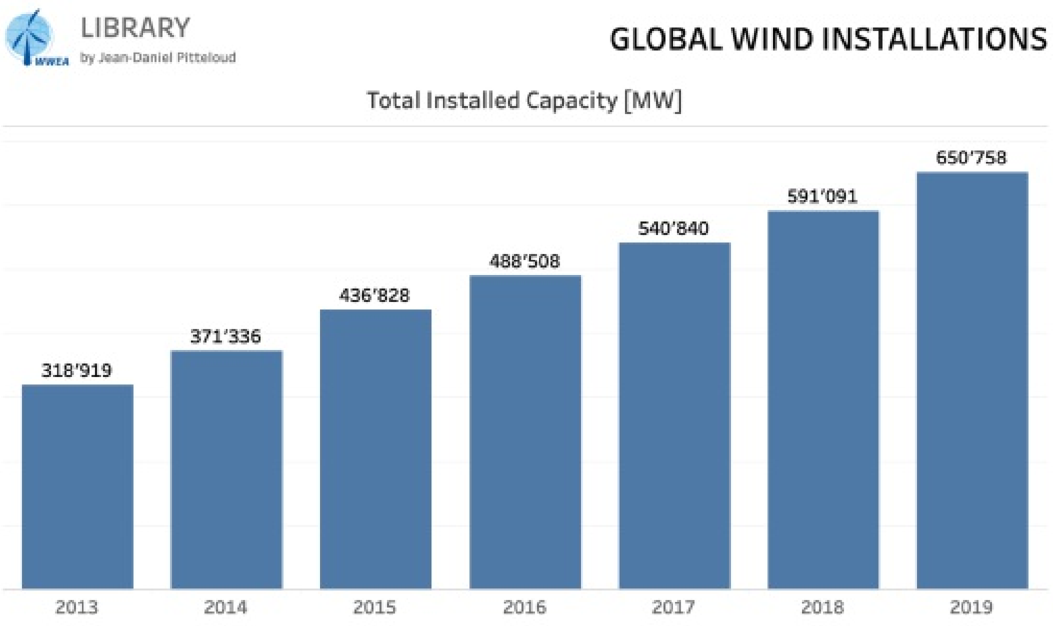
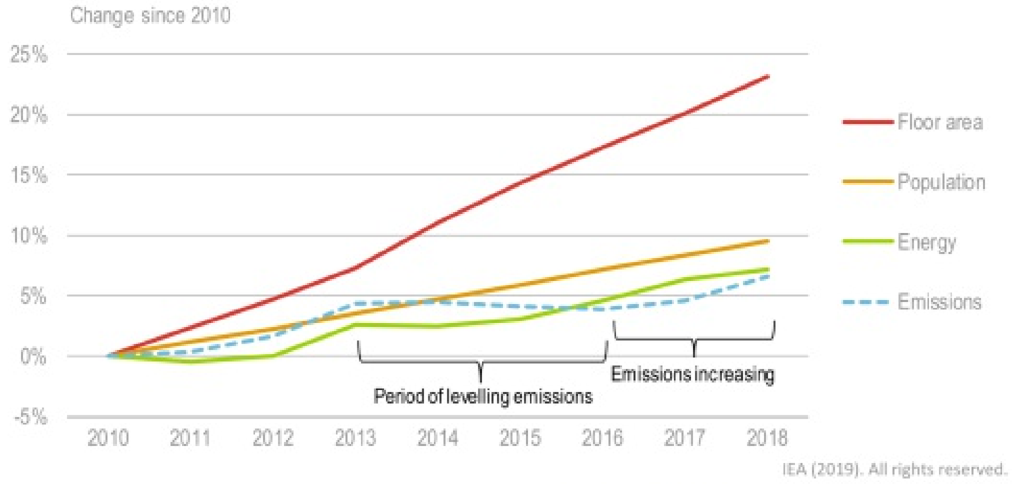


Figure 3 Total installed capacity of wind turbines (source: WWEA)

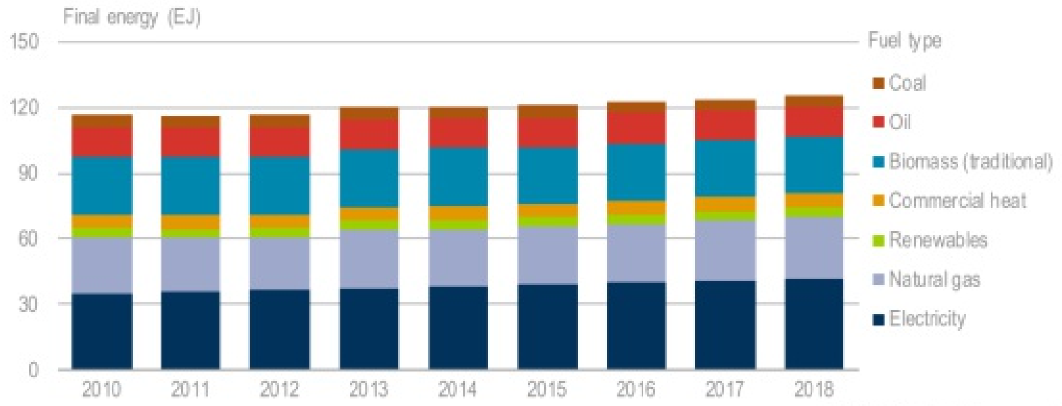
As reported at the IEA Global Status Report for Buildings and Construction, the global building stock emission keeps rising as the population grows. As seen on the graph below (Figure 4), there is a stable rise in population growth, energy use, and emissions in a period of 8 years, which means that this rise will keep happening in the following years.



Source: Derived from IEA (2019a), *World Energy Statistics and Balances 2019*, www.iea.org/statistics and IEA (2019b) *Energy Technology Perspectives*, buildings model, www.iea.org/buildings.

Figure 4 Global building stock emission (source: IEA 2019)

As shown in the graph below (Figure 5), the primary energy source for the final energy use of the global building sector is coal. However, during 2010-2018 renewable energy grew fast as an energy source for buildings and natural gas (IEA 2019).



IEA (2019). All rights reserved.

Notes: Energy data are not normalised for weather, so yearly energy changes may be due to climatic differences. Biomass (traditional) refers to conventional solid biomass (e.g. charcoal and forest or agricultural resources) used in inefficient heating and cooking equipment. Renewables includes solar thermal technologies as well as modern biomass resources (e.g. pellets and biogas).

Sources: Adapted from IEA (2019a), *World Energy Statistics and Balances* (database), www.iea.org/statistics and IEA (2019b), *Energy Technology Perspectives*, buildings model, www.iea.org/buildings.

Figure 5 Sources of energy in the building sector (source: IEA 2019)

The final energy consumption by end-use is mainly for space heating and water heating. However, the end-use that is increasing is the one for cooling (IEA 2019). That increase is logical, as global warming is influencing more and more cities. The report indicates:

“Factors influencing global buildings sector energy use include changes in population, floor area, energy service demand (e.g. more household appliances and cooling equipment), variations in climate and how buildings are constructed and used. Those that have contributed most to higher energy demand since 2010 are floor area, population and building use, while improvements in building envelopes (e.g. better insulation and windows) and in the performance of building energy systems (e.g. heating, cooling and ventilation) and components (e.g. cooking equipment) have helped to offset energy demand growth. Nevertheless, total energy demand in buildings continues to increase and greater investments in efficiency and passive design strategies are needed to limit demand and reduce energy intensity.”(IEA 2019, p.14)

Final energy consumption is affected by population growth. Floor area in urban settlements increases and remains the leading cause for higher consumption (IEA 2016). The continually increasing residential demand reflects the increase in population, an irreversible problem; therefore, solutions for lesser harmful building energy use needs to be implemented. There is a general shift away from the traditional use of energy sources like coal; however, to ultimately end coal use, more investments in renewables need to be set in motion. Therefore, small wind turbines can prove advantageous to the demands of the city.

1.3.3 Advantages and Disadvantages of Small Wind Turbines

The advantage of small wind turbines is that they are versatile and take up minimal space, compared to traditional wind turbines or photovoltaic panels that need acres of land to exploit their potential (Ishugah et al. 2014). Small wind turbines can come in different shapes and can be implemented on diverse areas, like buildings, parks, or even highways, and on top of street lamps to minimize street lighting consumption (Heo et al. 2016). However, there are downsides to incorporating a source of electricity in cities and on buildings, because the technology can cause various issues on structures and the ambient of the city.

Small Wind Turbines can be installed either off-grid or on-grid. On-grid installation means that the building is still connected to the traditional energy supply grid and will receive energy from it, if necessary. On-grid happens by lending power back to the grid when the turbine produces more than the consumption. On the other hand, off-grid signifies the dwelling's complete autonomy, with power being stored in battery cells. Whichever technique is chosen, it will decrease the cost of energy consumption and CO_2 emissions. (Gsänger and Pitteloud 2015)

As mentioned in this review's historical part, there are two types of urban and building-integrated wind turbines: Horizontal and Vertical Axis turbines. However, particular interest exists in the turbines' vertical modification because it can be implemented without the requirement to face the wind's direction. The unique design of a vertical axis turbine allows the turbine to capture wind from any direction, making it easier to augment on buildings (Casini 2015) .

Several advantages can come with the installation of small wind turbines:

- Turbines do not produce emissions that damage the environment, creating clean energy (Main 2013).
- It encompasses a renewable source's financial advantage, creating energy for no cost (Saeed 2017).
- As it happens with most renewable energy options, the installation cost's payoff period can only be a few years (Cooney et al. 2017).
- When connected to the grid, additional energy can be sold to the local energy company (on-grid application) (Gsänger and Pitteloud 2015).
- Several countries offer tax incentives (Gsänger and Pitteloud 2015).
- Compared to PV panels, wind turbines operate more or less at 30% capacity, while the latter at only 15% (Gsänger and Pitteloud 2015).

However, some downsides may lead potential buyers to decide against installing a small wind turbine to their household or community as with any new technology. Such negative aspects are sound pollution and oscillations, especially in building-integrated turbines (Saeed 2017). A summary of what Saeed (2017) refers to as disadvantages in his paper is:

- Initial installation is costly.
- In some areas, the use of wind may be regulated.
- Wind turbines cannot operate without wind.
- They produce noise.

Some adequate solutions to the problems that Saeed is referring to are:

- For installation cost, one should have a fund set up (Blanco 2009).
- For regulations, it is needed to check with local authorities before installing (Blanco 2009).
- For wind potential, it needs to be specified that the place of installation can provide adequate wind. The World Meteorological Organization provides an interactive world atlas for wind speed (B. R. Dymock n.d.).
- For minimum noise, in the specifications of each model, the noise produced is indicated. Therefore, according to the distance between the installation spot and the building or park (Saeed 2017), a choice can be made.

Whether as a financial motive or an environmental concern, wind turbines, despite their disadvantages, can be an efficient solution to the ongoing problem of supplying buildings with energy without producing CO_2 emissions. Small wind turbines can add to large-scale wind farms as long as wind conditions in the city are favorable.

1.3.4 Urban Wind Conditions

What distinguishes an urban from a rural area is the presence of structures. These structures influence the urban wind regime because they form an uneven topography, which causes the wind -on an annual basis- to exhibit lower wind speeds than the rural area (Ishugah et al. 2014). The atmospheric boundary layers over a city have a more turbulent flow due to constant directional wind changes because of interference with building surfaces (Anup et al. 2019).

Understanding the wind speeds in a rural area and how they form modeling wind around buildings is the best tool. However, two-dimensional modeling of wind flow around buildings is not as representative as the 3D. Because when a tall building- in a wind flow representation- is preceded by a lower building, then the latter trips off a vortex in the space between buildings. Therefore, air descending close to the windward wall flows through openings beneath the building at ground level. Moreover, accelerated flow is produced, which causes regions to form around vertical and horizontal corners of the building. In the areas of vortex- flow, through-flow, and corner streams, many design problems are presented by the locally accelerated flow's unique characteristics. (Simiu and Scanlan 1996)

In addition, to clarify Simiu and Scalan's (1996) conclusions, in Figure 6, there is a graphical representation of how wind speeds vary in speed and direction due to the presence of upstream obstacles and the effect of turbulence at average wind speed. Moreover, when SWTs are installed in the built environment, there is limited understanding of the installation location's wind conditions and the wind turbulence caused by the surrounding topography. Such atmospheric turbulence is superimposed on the wind's average motion. It impacts the wind energy converter (WEC) in many ways, e.g., unexpected downtimes due to failure during operation, fatigue damage, inconsistent power output, etc. Even though there is an advanced manufacturing process and design techniques of wind turbines, the physics of turbulent wind in the built environment and its related statistics during interaction with SWTs are still not considered sufficiently. Lack of understanding of local wind conditions produced by wind interactions with localized structures has resulted in poor siting, and improper use of such SWTs impedes safety, durability, and performance. (Anup et al. 2019)

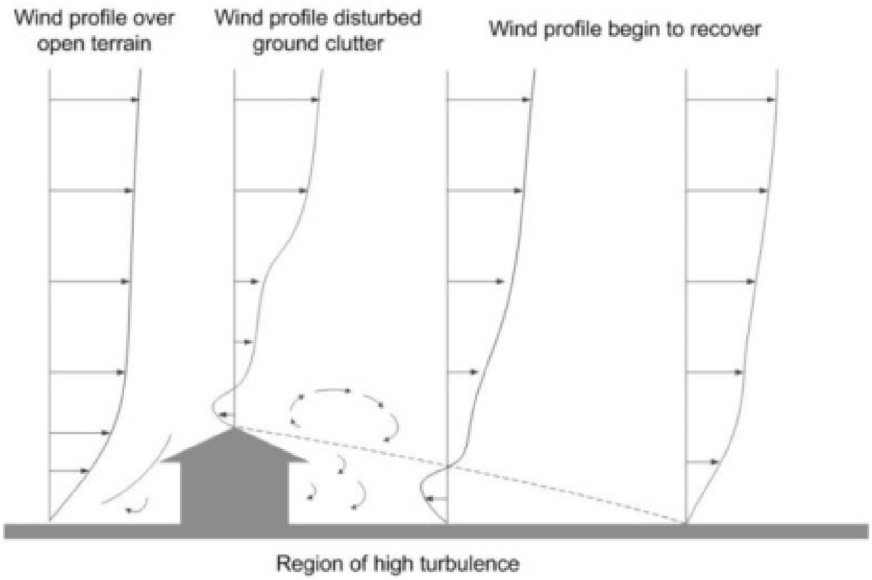


Figure 6 Wind flow around buildings (Source: Anup et al. 2019)

Looking closer into the City of Vienna, it is evident that the wind speeds are lower in the city, where many shapes influence the wind patterns, as mentioned earlier. More specifically, the city provides map information about the power density of wind and illustrates that it has a medium to low wind density, as illustrated in Figure 7.

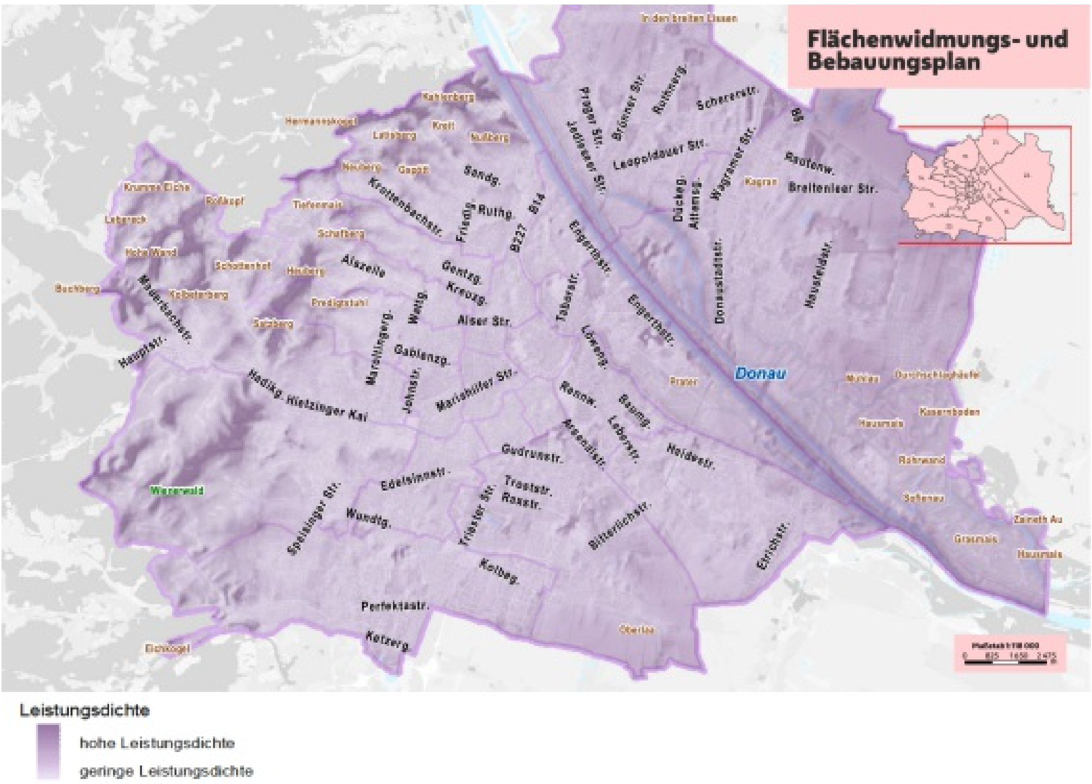


Figure 7 Power Density of wind in the city of Vienna (Source: Stadt Wien)

Vienna's lower wind capacity results from the existence of buildings and the city's geographical location (Vienna being surrounded by mountains). More specifically, Vienna has a moderate windspeed energy potential, with windspeeds variating between 2,5 - 4m/s (Figure 8).

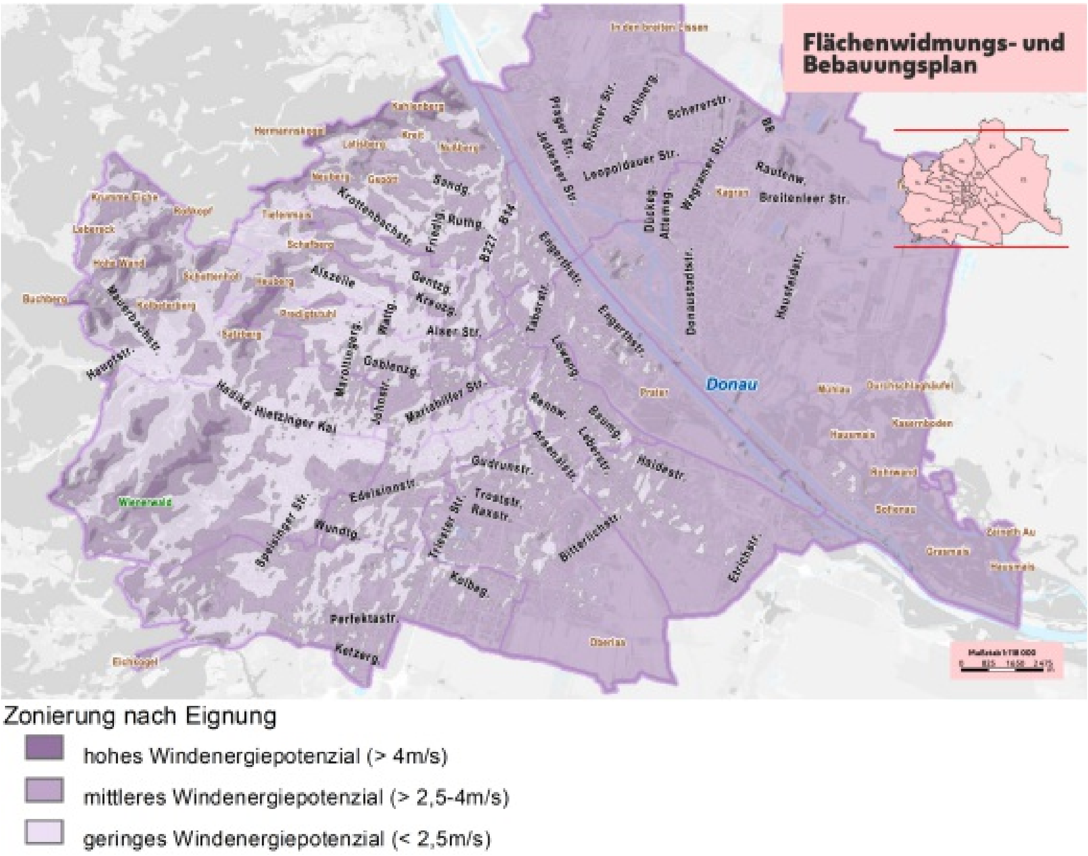


Figure 8 Wind Energy Potential in the city of Vienna (Source: Stadt Wien)

For the scope of this thesis, in addition to a literature review of the currently available research, an estimation of the potential of the city of Vienna to produce wind energy through the installation of small wind turbines on flat roofs of buildings will be calculated.

2 APPROACH

The central element of the Master thesis is to investigate the current research, the technical specifications, and the implementation and benefits of small wind turbines in cities. Thus, the method used to conclude this Master thesis is a comprehensive literature review and a rough estimation of the electricity production from small wind turbines in Vienna. A literature review aims to collect and represent data of studies, books, journals, and conference papers.

The best method to provide the information to answer the research question and create a handbook for small wind turbine advancements would be a literature review. Because -through that method- the knowledge over the topic can be gathered in one place.

The criteria for selecting the literature are:

- **The relevance of the paper**; the paper must be relevant to the keyword search.
- **Method of the paper;** included methods are numerical simulations, feasibility studies, comparative analysis, and literature review
- **Year of publishing**; The papers chosen are after the year 2016

Moreover, keywords used for search engines are:

- *Small Wind Turbines*
- *Efficiency*
- *Position*
- *Design*
- *Performance*
- *Noise*
- *Return on investment*
- *Payback*

Keywords are essential to organize the research through the sources of information. Moreover, through the combination of criteria and keyword search, the literature review is optimized.

2.1 Sources of Information

A scientific review requires the collection and analysis of relevant scientific research publications. Sources for the Small Wind Turbine literature review come from a variety of places:

- **Books:** The TU Library was the source of book material. Renewable energies and building performance books were used.
- **Reference Materials:** Encyclopedias and dictionaries were used to elaborate on terms for energy and wind turbines.
- **Journals:** Were important source of updated material.
- **Conference Papers:** Helped to review the latest news on the technologies
- **Dissertations and Theses**: Were used as a source of information and structure.
- **International Organization Publications:** Were used for material regarding energy demand and weather conditions. Moreover, data from the city of Vienna (Stadt Wien) and Austria's statistical database (Statistik Austria) were used for the rough estimation of wind energy potential.
- **Manufacturer websites and personal contact:** Most manufacturers provide factual information for their products. Where the specifications were not covered, then online contact was mandatory.

2.2 Categories of Sources of Information

It is essential to identify and categorize the sources that one uses to research a scientific question. The categorization of information sources has helped structure the review logically. There Thesis research is covered by three parts that are analyzed below.

Present Technologies

The state of the art of emerging technologies has changed in the past years. SWTs have become more durable and produce energy at lower wind speeds. The manufacturer scene is changing fast, and emerging technologies form a new reality. Consequently, manufacturers were contacted to verify the continuation of their businesses and collect data that were missing from their websites.

For the present technologies, a comparison is made between specifications. Moreover, to present a concrete argument for the financial benefit of the investment, EU electricity prices are used to calculate the return on investment in a period of 20 years.

Cost calculation is performed to analyze the technology's investment benefit in 3 brands of turbines (brands that provided sufficient data to implement the calculation). The calculation takes into consideration the following aspects:

- Maintenance Cost at 10% of the purchase cost
- Life Expectancy of the Turbine at 20 years
- Labour cost per day at 50 euros
- Supervision of the turbine for four days per year (information of how many times a turbine needs supervision in a year were provided by only one brand and were considered as the same for the rest)

Furthermore, with the data mentioned above into consideration, the cost calculation encompasses the:

- Capital cost
- Maintenance
- Supervision
- Total cost per year

The operational data are then considered; hence, the kilowatt hours that each turbine produces under different wind speeds (6-9 m/s). The data are derived from the graphs on yearly output per windspeed that manufacturers provide. From the operational data, the ratio of cost (in Euro)/ kWh is calculated. The final graphs are produced by the data of variance cost per EU country and the cost Euro/kWh ratio.

Case Studies

Case studies comprise an articulate example of the implemented technology and showcase their advantages and disadvantages—the aspects where SWTs succeeded and where it did not.

Scientific Research; Papers

Scientific papers present recent technologies' tendencies and explain the current situation regarding the Small Wind Turbine (SWT) technology and advancements in the field. By investigating scientific research, the questions to the original hypothesis are answered.

The dominant questions regarding SWT scientific research are:

- What is the efficiency of small wind turbines?
- How much noise do they produce?
- What is the optimum place on a building for maximum efficiency?
- Is the investment worth doing?

The literature review is organized in a table of topics, which gives an overview of the written review that follows. The topics are sort by type of thematic category, and the papers are analyzed in the discussion part of the thesis and compared with the calculation results of parts 2 and 3.

Moreover, a rough calculation is performed for the city of Vienna to showcase the city's wind power generation capacity. For the calculation of Vienna's wind potential, data are derived from the city of Vienna. The data for wind classification of areas can found in the Open Data Österreich website ("Offene Daten Österreich | Data.Gv.At" n.d.) and the map that illustrates the information from the Stadt Wien website ("Wien Umweltgut" n.d.). Also, Vienna's flat roof percentage was found in a dissertation from the Technical University of Vienna (Dang et al. 2019).

More specifically, the classification of wind speed is done in three categories:

1) High wind energy potential (> 4m/s)
2) Medium wind energy potential (> 2,5-4m/s)
3) Low wind energy potential (< 2,5m/s)

The energy that one wind turbine can produce is derived from the results of part 2 cost calculation; the estimation is made about installing different amounts of small wind turbines on the buildings and the electricity produced in total in the city by the installed turbines. Lastly, the percentage of the city's electricity coverage is calculated, as well as the cost of electricity produced by the turbines.

In the Review chapter the data are organized and graphs resulting from calculations are presented. More specifically, data from manufacturers are gathered, and graphs are produced to visualize the critical specifications that influence the technology's final choice. Moreover, the rough estimation is presented to showcase the potential of the city to become a wind farm.

In the Discussion section, the information from the overview is further explained, and through critical thinking, the results of similar studies are compared. In addition, the manufacturers' data are compared with the literature review findings and the rough estimation for Vienna's small wind turbine potential.

3 REVIEW

In this chapter, the SWT technical information is presented, followed by the state of the art examples. Furthermore, the papers and books that show the current trends in research and development are reviewed. In addition, using the knowledge from the technical information findings, return on investment is calculated and a rough estimation of Vienna's capacity for small wind turbine installation is performed.

Overall, the information presented in this chapter will be illustrated through explanatory text, tables and graphs. Hence, in this chapter, there will be condensed information, while in the next chapter, those outcomes will be further discussed.

3.1 Small Wind Turbine Innovations

In the past years, the suppliers of Small Wind turbines have transformed since electricity prices, and other renewable alternatives have influenced the technology. The current technologies aim to provide high performance in low wind speeds and design that can be harmonically incorporated in cities.

Further analysis of the existing technologies shows that research and development are fruitful to the industry. More specifically, new products focus on:

Rotor:

- A rotor that adjusts RPMs to the turbine's needs (Kliux n.d.)
- Low maintenance systems to be used on-grid or off-grid (Fortis Wind Energy n.d.).
- Stand-alone hybrid systems (Fortis Wind Energy n.d.).
- A unique feature of not needing a multiplier, since it is connected to the rotor (ENERCON 2016), makes the turbine more modifiable for the city's energy needs.
- Lightweight and quiet turbines that allow for retrofit when it exceeds its life expectancy (Techcarbon 2017).

Materials:

- Producing SWTs with corrosion-free materials, which makes the product durable (Aerocraft 2016).
- Using carbon fiber for the parts that make the turbine light (Quiet Revolution 2020).
- A design that helps the turbine remain at low dB when producing energy (Kessler SPINWIND 2020, Renewable Devices n.d.).

Windspeed:

- Implemented control systems and breakage for high wind speeds to be low maintenance (AEOLOS 2020).
- Adaptability to high wind speeds by automatically reducing rotational speed, therefore making them more durable (Marlec 2020).
- Using Darrieus type turbines that do not require wind to hit it only from one direction and can withstand and start with multiple wind directions. (V-Air 2018).
- Start at low wind speeds (Vertical Wind n.d.) because that will help the usage in cities that do not provide satisfactory wind conditions.

Dimensions:

- Size adaptable Horizontal Axes Wind Turbines (HAWT) that are designed to be placed in open fields and be installed for domestic use (Bergey WindPower n.d.).
- SWTs that have a more significant swept area, and therefore can capture more wind and produce more power than the usual SWT (RyseEnergy 2020)
- Providing a variety of sizes and provide different propeller diameters that operate at very low wind speeds (Braun Windturbinen 2013).

Additional components:

- A shrouded wind turbine can be half the size of a usual SWT and provide twice the efficiency in producing energy (Halo ENERGY n.d.) because the duct accelerates airflow.
- Adopting a ducted wind turbine design (SINNPOWER 2019) to optimize wind flow on the blades. Wind will be harvest without losses because the wind velocity will be increased when entering the duct.

Digitalization:

- Online applications that makes it easy to adjust to each country's codes for energy production (Quiet Revolution 2020).
- Provide access to cloud-based platforms that allow monitoring of energy production. Such technology offers online access to each installation's performance data (SINNPOWER 2019) and favors efficient maintenance.
- Applications that allow the SWT owner to monitor and control the turbine's performance (Bornay 2017) and provide a sense of security to the owner.

- On-site assessment makes it easy to identify the best possible solution for SWTs and produce both versions of SWTs, hence providing horizontal and vertical solutions (Brit Wind n.d.).

Innovative designs:

- The innovative wind turbine tree of New *World Wind* (Figure 9) is most suitable for cities. Its design and aesthetics constitute it as the easiest way to incorporate wind turbines in a city. The mechanism that rotates the leaves does not have gear or belts; hence it is noise-free. Also, the leaves start rotating at very low speeds. Moreover, it is adjustable, meaning that one could determine their energy needs and, therefore, the number of leaves. (New World Wind 2020)

Figure 9 New World Wind Tree "Planted" in Velizy, France (source: New World Wind 2019)

To sum up, the available technologies in the market showcase that there are efforts to enhance small wind turbines and turn the public opinion about them being inefficient. In the following sub-chapter, the specifications are illustrated in detail.

3.2 Small Wind Turbine Specifications

Small wind turbines come with several specifications that present their ability to generate energy, as well as the size and height that they cover. More specifically, to understand each part's contribution to the performance, a regular turbine's essential components are illustrated in Figure 10 and Figure 11. Moreover, small wind turbines have the same characteristics as regular-sized turbines; therefore, the used figures are from a typical turbine. Functionality stays the same, but the size changes. In addition, from the figures below, mechanical parts are responsible for generating power, whereas electrical parts are essential to transmitting power.

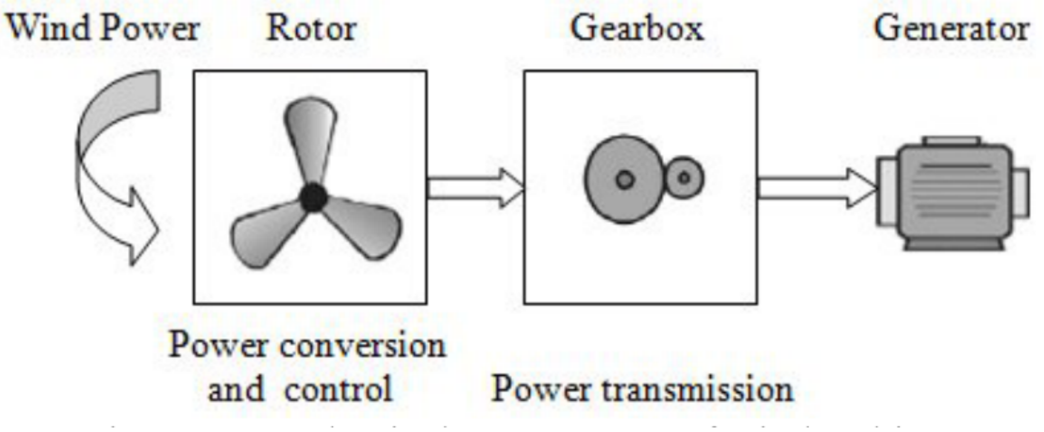


Figure 10 Mechanical parts of a wind turbine (source: Sarkar 2012)

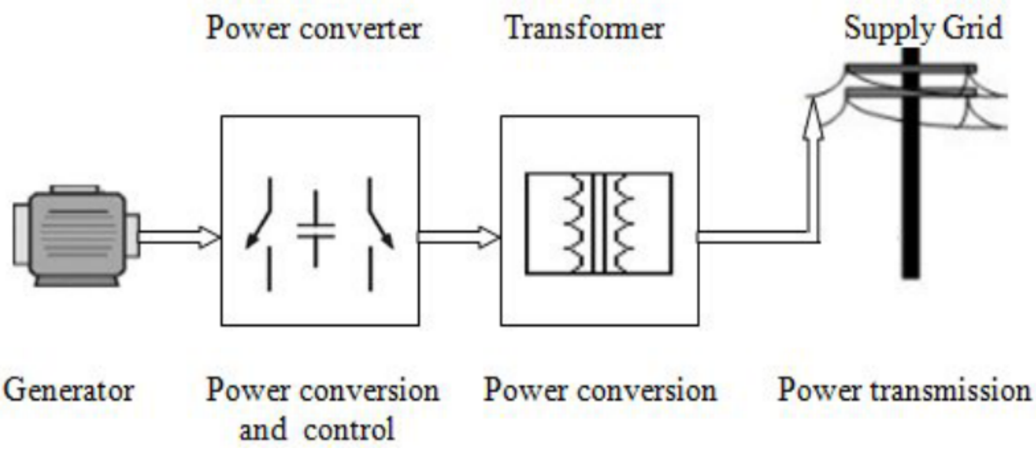


Figure 11 Electrical parts of a wind turbine (source: Sarkar 2012)

An essential factor of wind turbines' function is the circular area that the blades are covering, also known as the swept area (Figure 12). The swept area differs in a small wind turbine as the dimensions are reduced. However, the philosophy behind it is the same as in a typical wind turbine. As the blade turns, it sweeps the air.

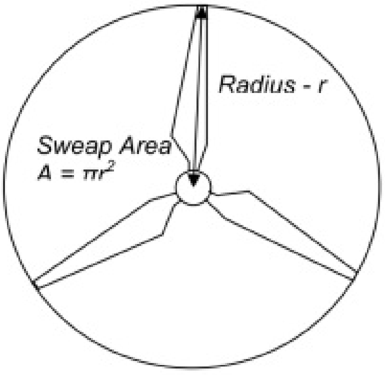


Figure 12 Turbine blade's swept area (source: RWE 2007)

In the following sub-chapters, the specifications for the efficient function of a small wind turbine are explained.

3.2.1 Rated Power

Rated Power is the peak power that a turbine can produce (Sarkar et al. 2012). The amount of power that the SWT was designed to produce depends on the speed of the wind, the arrangement, and the amount of time the turbine is undergoing maintenance and is not available to produce power (Sarkar et al. 2012). Moreover, the Betz limit sets the turbine's capacity to transform kinetic energy to power at 59% of wind force; therefore, any turbine has a limit of 59% to derive energy from the wind (RWE 2007). The limit mentioned above is also known as the power coefficient and is given by the number:

C_p= 0,59

Moreover, the power equation for a wind turbine is including the power coefficient and given by the equation (RWE 2007):

$$\mathbf{P_{avail}} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\rho}\mathbf{A}\mathbf{v}^{\mathbf{3}}\mathbf{C_p} \qquad (1)$$

where:

ρ: Density (Kg/m^3)

A: Swept Area (m^2)

V: Windspeed (m/s)

C_p: Power Coefficient

3.2.2 Tower Height

Tower height is the height that the rotor and blades are located. For many turbines, it varies, with some having fixed tower values. Moreover, as tower height increases, so does the wind speed. Furthermore, the relation between height and wind speed comes from the wind profile one-seventh power law, which indicates that:

"the wind speed increases proportionally to the one-seventh root of height above the surface" (Dixon et al. 2014, p.426)

$$\frac{c_x}{c_{x_{ref}}} = \left(\frac{h}{h_{ref}}\right)^n \qquad (2)$$

Where:

c_x: Windspeed at height h

h: Height

h_{ref} : Reference height

$c_{x\ ref}$: Windspeed at a reference height

n: empirically derived coefficient, n=0.143 under stable atmospheric conditions

3.2.3 Rotor Diameter and Swept Area

Rotor Diameter is used to estimate the power output of the turbine. The rotor diameter encompasses the diameter of blades, which ultimately translates to the swept area, hence the area that the blades occupy to sweep air (Can et al. 2020). Moreover, as rotor diameter is related to wind velocity and power output (relation given in the equation in 24), it is evident that the energy output rises with the rise of the swept area.

3.2.4 Cut-In Wind speed

Cut-in wind speed is the wind velocity required for the blades to start rotating and generate power. Weather stations in the area can extract wind speed data; however, for more accurate data, a wind measuring device can be placed at the point of SWT insertion.

3.2.5 Yearly energy Output

Yearly energy output determines the average energy produced by a turbine in a period of 12 months. The yearly energy output is calculated by acquiring windspeed data with very small-time spam between them from the location that the turbine is placed. The location weather conditions change; therefore, to calculate the energy output, a statistical model for mean wind velocity is calculated. The most known method to calculate the mean wind velocity is using the Weibull distribution (Popovac 2012). The equation to calculate the yearly energy output as given in the small wind guidebook (Can et al. 2020) is:

$$AEO = 0.01328\, D^2 V^3 \qquad (3)$$

Where:

AEO: Annual energy output (kWh/year)

D: Rotor diameter (meters)

V: Annual average wind speed (Km/h)

3.2.6 Sound Emission

When the rotor is active, it produces a certain amount of sound. That sound - depending on how loud it is- can be bothersome to the public. Sound pollution of small wind turbines is calculated between 50-60 dB (Hodgson 2004). Moreover, countries worldwide have different noise limits inside cities; a conclusion according to an IEA meeting is that the maximum limit in the EU is 50 dB (Johansson 2000).

3.2.7 Comparison of Available Technologies

Following the explanations of SWT specifications, a comprehensive list of manufacturers and specification data is presented in this section.

From the data listed in the tables below (Table 1-Table 5), it can be noticed that the majority of the companies produce Horizontal Axis turbines, and their rated power does not exceed- in most cases- 10000 watts. Since small wind turbines are supposed to be versatile in terms of at which height they will be placed. As buildings vary in total height; hence, they provide a variety of tower height.

Moreover, the rotor diameter plays a role in wind turbines because it can determine the energy that can be extracted. A larger rotor means a larger swept area; hence the turbine captures more wind and produces more energy. Since SWTs need to maintain a relatively small diameter, larger rotors are not preferred when manufacturing turbines for urban use (Table 1-Table 5). The most standard diameters are between 2 and 5meters.

Table 1 List of small wind turbine companies and specifications

Manufacturers	Country	Type	Model	Rated Power (Watt)	Tower Height (meters)	Rotor Diameter (m)	Cut-in Wind Speed (m/s)	Survival Wind Speed (m/s)	Yearly Energy Output (kWh)	Price (euro)	Sound Emission (dB)
			h 500w	500	2	2,7	2,5	45	n.d.	n.d.	25
			h 1000w	1000	2	3,2	2,5	45	n.d.	n.d.	30
		Horizontal	h 2000w	2000	4	4	2,5	45	n.d.	n.d.	35
			300w	300	4	1,2	1,5	50	n.d.	n.d.	45
			600w	600	6	1,6	1,5	50	n.d.	n.d.	45
			1000w	1000	6	2	1,5	50	n.d.	n.d.	45
Aeolos	DK	Vertical	3000w	3000	6	3	1,5	52,5	n.d.	n.d.	45
			Hoyi	200	1,3	0,8	2,5	50	n.d.	n.d.	n.d
			vision air 3	2000	3,2	1,8	4	50	2800	n.d.	41
uge v-air	US	Vertical	vision air 5	3000	5,2	3,2	3,5	50	9000	n.d.	38
			excel 10	8900	varies	7	2,5	60	13800	n.d.	42,9
Bergey wind power	ES	Horizontal	excel 15	15600	varies	9,6	2,5	60	29800	n.d.	48,5

Table 2 Table 1 Continued

Manufacturers	Country	Type	Model	Rated Power (Watt)	Tower Height (meters)	Rotor Diameter (m)	Cut-in Wind Speed (m/s)	Survival Wind Speed (m/s)	Yearly Energy Output (kWh)	Price (euro)	Sound Emission (dB)
Britwind	UK	Horizontal	H15 class2	16000	14,5	10,4	n.d.	60	65313	n.d.	88,6
			H15 class5	12000	18	13,1	n.d.	42	48703	n.d.	89,4
Marlec	UK	Horizontal	Rutland FM910-4		varies	n.d.	3	n.d.	400	828,82	n.d.
			Rutland 1200		varies	n.d.	2,5	n.d.	800	1533,41	n.d.
			Rutland FM1803		varies	n.d.	3	n.d.	1350	2770,72	n.d.
Renewable devices	UK	Horizontal	swift wind	1500	varies	2,12	3,4	n.d.	2000	1598,53	34
Aerocraf	DE	Horizontal	AC 120 & AC 240	240	varies	1,65	3	40	n.d.	n.d.	n.d.
			AC752	700	varies	2,4	3	40	n.d.	n.d.	n.d.
			AC 1002 H	1000	varies	2,4	3	40	n.d.	n.d.	n.d.

Table 3 Table 1 Continued

Manufacturers	Country	Type	Model	Rated Power (Watt)	Tower Height (meters)	Rotor Diameter (m)	Cut-in Wind Speed (m/s)	Survival Wind Speed (m/s)	Yearly Energy Output (kWh)	Price (euro)	Sound Emission (dB)
			350/353	350	varies	1,22	3,5	n.d.	n.d.	n.d.	n.d.
Superwind	DE	Horizontal	1250	1250	varies	2,4	3,5	n.d.	n.d.	n.d.	n.d.
			Passaat	1400	varies	3,12	2,5	60	3200	n.d.	n.d.
			Montana	5000	varies	5	2,5	60	9500	n.d.	n.d.
Fortis Wind Energy	NL	Horizontal	Alize	10000	varies	6,9	3	60	22000	n.d.	n.d.
			Wind 13+	1000	varies	2,65	3	60	n.d.	n.d.	n.d.
			Wind 25,2+	3000	n.d.	4	3	60	n.d.	n.d.	n.d.
			Wind 25,3+	5000		4	3	60	n.d.	n.d.	n.d.
Bornay	Global	Horizontal	BEE 800	n.d.	varies	n.d.	3,5	60	n.d.	n.d.	n.d.
Gaia Wind	DE	Horizontal	133-11KW	10000	varies	13	3,5	n.d.	46527	n.d.	n.d.
Kliux	ES	Vertical	GEO 1800	1800	varies	2,36	3,5	n.d.	9170	n.d.	33

Table 4 Table 1 Continued

Manufacturers	Country	Type	Model	Rated Power (Watt)	Tower Height (meters)	Rotor Diameter (m)	Cut-in Wind Speed (m/s)	Survival Wind Speed (m/s)	Yearly Energy Output (kWh)	Price (euro)	Sound Emission (dB)
			Antaris 2.5KW	2700	varies	3	3	n.d.	n.d.	n.d.	n.d.
			Antaris 3.5KW	3700	varies	3,5	3	n.d.	n.d.	n.d.	n.d.
			Antaris 5.5KW	6000	varies	4	3	n.d.	n.d.	n.d.	n.d.
Braun Windturbinen	DE	Horizontal	Antaris 7.5KW	7500	varies	5,3	3	n.d.	n.d.	n.d.	n.d.
Halo Energy	US	Horizontal	halo 6kw	6000	varies	2,4	2,5	60	24835	13.000	n.d.
Venturicon	AU	Horizontal	zero wind turbine	1150	varies	1,9	2,5	60	n.d.	n.d.	45
Ergycon	IT	Horizontal	ely50	50000	24	20,7	2,5	n.d.	n.d.	n.d.	n.d.
Quiet Revolution	UK	Vertical	Qr6	n.d.	varies	n.d.	1,5	n.d.	n.d.	n.d.	54
Sauer Energy	US	Vertical	Wind Cutter	1500	varies	2,31	4	45	3460	n.d.	n.d.

Table 5 Table 1 Continued

Manufacturers	Country	Type	Model	Rated Power (Watt)	tower height (meters)	Rotor Diameter (m)	Cut-in Wind Speed (m/s)	Survival Wind Speed (m/s)	Yearly Energy Output (kWh)	Price (euro)	Sound Emission (dB)
Kessler	DE	Vertical	Spinwind	10000	varies	4,7	3	37,5	n.d.	n.d.	35
Free Tree	AU	Vertical	free tree	n.d.	varies	n.d.	3,4	n.d.	n.d.	n.d.	n.d.
New World Wind	FR	Misc	The Wind Tree	n.d.	varies	n.d.	2,5	43	10800	49680	n.d.
			The Modular Tree	n.d.	varies	n.d.	2,5	43	10275	26900	n.d.
Wind of change	DE	Vertical	The Wind Bush	n.d.	varies	n.d.	2,5	43	4212	19500	34
			Helix 3500	3500	varies	1,75	2,8	n.d.	n.d.	n.d.	32
Wind of change	DE	Vertical	Helix Wind Turbine 1400	1400	varies	1,75	2,8	n.d.	3000	n.d.	32

3.3 State of the Art in Small Wind Turbines

A plethora of buildings and city wind turbine projects have implemented the technology of SWTs. Among those, several noteworthy projects (see Table 6 and Table 7) can be singled out to be explored in-depth as case studies. Studies that focus on these projects will be examined in the following chapter.

Table 6 State of the Art technicalities

Name	**Location**	**Specifications**
Strata Tower	London, UK	Building height: 148m Number of Turbines: 3 Axis of turbine: Horizontal Turbine diameter: 9m Construction completed: 2010 Expected Annual Energy Yield (AEY): 50 MWh Source: (Schwartz 2010)
Bahrain World Trade Center	Manama, BH	Building height: 240m Number of turbines: 3 Axis of turbine: Horizontal Turbine diameter: 29m Construction completed: 2008 Expected Annual Energy Yield (AEY): 1.1-1.3 GWh Source: (Smith and Killa 2007)
Pearl River Tower	Guangzhou, CN	Building Height: 309.6m Number of turbines: 4 Axis of turbine: Vertical Turbine diameter: 5m X 2m (Height X Width) Construction completed: 2011 Expected Annual Energy Yield (AEY): Not defined Source: (Yip 2010)

Table 7 Table 6 continued

Name	Location	Specifications
Highway Vertical Axis Generators in Highways	Kurdistan	Specifications: Not defined Source: (Ibrahim 2019)
Our Lady of Providence Girls’ High School	New Taipei, TW	Specifications: Not Defined Source: (Ministry of Foreign Affairs, Republic of china (Taiwan) 2013)
CIS Tower	Manchester, UK	Turbine tower height: 3m Number of turbines: 24 Axis of turbine: Horizontal Expected Annual Energy Yield (AEY): 56000 Units Source: (BBC 2005)

Strata Tower was a very ambitious project from the city of London as it was expected to reduce carbon emissions. The estimation for anticipated power generation from the turbines integrated into the structure was 8% of the building’s energy needs (Schwartz 2010). The tower's design incorporated the turbines on the top levels (Figure 13)(Teh 2016), where wind harvest is most efficient (Kompatscher 2015).

Figure 13 Strata Tower, London (source:Teh 2016)

Contrary to Strata Tower’s philosophy; of positioning turbines on the top of the building, the Bahrain World Trade Center (Shahin 2020) has implemented various turbine placement heights (Figure 14).

Figure 14 Bahrain World Trade Center, Manama (source: Shahin 2020)

A sleeker design was adopted in the Pearl River Tower (Yip 2010), where the turbines are not visible from the exterior but rather hidden between the floors of the tower (Figure 15).

Figure 15 Pearl River Tower, Guangzhou (source: Yip 2010)

Moreover, smaller-scale projects (Figure 16, Figure 17, Figure 18) showcase that it is unnecessary to have a new large scale development to install small wind turbines. In Manchester, small wind turbines were installed on the top of the existing CIS Tower (Figure 16) and expected to produce 56000 units annually (BBC 2005).

Figure 16 Small wind turbines installed on CIS tower in Manchester, UK (Source: BBC 2005)

Figure 17 Small wind turbines installed on the rooftop of ROC (Source: Ministry of foreign affairs, Republic of China (Taiwan) 2013)

Figure 18 Project for small wind turbine integration on a rooftop (Source: Building-integrated wind turbines 2016)

State of the art examples illustrate how small wind turbines can be incorporated in the urban canopy layer without being visually disturbing to citizens, because their size allows them to be easily camouflaged (e.g. by placing them on flat roofs). However, some restrictions in integrating small wind turbines on buildings will be discussed in the following chapters.

3.4 Review of Scientific Papers

Studies globally are looking for methods to enhance the performance of SWTs, with research focusing on the design of the blades, rotor performance, solidity, and how many blades will be placed on the turbine. In addition, the position of the turbine plays a crucial role in establishing a profit for SWTs. Moreover, the profit of having an SWT investment is an area of research that can prove the viability of the investment.

In the following chapters, the most important research literature findings in new technologies are distributed in tables according to thematic classification. A list of the titles of the papers and books considered for this literature review can be found in the Appendix pages 88-93.

3.4.1 Performance and Design of Small Wind Turbines

Performance is changing according to the type of turbine (Vertical or Horizontal), the number of blades, as well as their design. Computational Fluid Dynamics (CFD) help investigate the alterations in performance when the factors mentioned above change. Therefore, as observed in the tables below (Table 8, Table 9 and Table 10), many researchers use CFD to study the performance of SWTs.

Table 8 Scientific papers for SWT performance

Author(s) & Year	**Purpose**	**Method & Tool**	**Results**
ElCheikh et al. 2018	The paper investigates the performance of Orthopter-type Vertical Axis Wind Turbines in relation to solidity and number of blades.	Numerical Simulation DDES in Spalart Allmaras Model	Higher solidity helps boost the power coefficient. The tip speed ratio is influenced by wind speeds, which correlates to the power coefficient. Three bladed turbines perform to produce a higher power coefficient. More blades and a lower aspect ratio perform better in extracting power.
Manganhar et al. 2019	This paper proposes a Rotor House vertical axis wind turbine and tests it under laboratory and open-air conditions, with rotor house and without.	Comparative Study	A rotor with a Rotor House performs better and improves efficiency to more than double the bare rotor. In environmental conditions, turbulent flows decrease the performance of the turbine.
Wang et al. 2008	Optimize the aerodynamic design of an SWT for urban use.	Numerical Analysis ANSYS Fluent	Results showcase that connection methods do not affect the performance a lot. The annual performance is affected by meteorological state and urban morphology. Therefore simulations that were carried out with the assumption that wind is stable (a common assumption for large wind turbines) do not showcase the actual yield as it should be.

Table 9 Table 8 continued

Author(s) & Year	Purpose	Method & Tool	Results
Rezaeiha et al. 2018	The study focuses on Vertical Axis Wind Turbines and how differences in solidity and number of blades influence the performance. The unique design conditions that have an impact on the performance are studied.	Numerical Study ANSYS Fluent	For small to medium-size wind turbines, solidity is advised to remain low. The paper gives a holistic design for the performance view. More blades equal more power and rigid loads.
Arteaga-López et al. 2019	Present a methodology that can be applied in various CFD calculations for SWTs in urban environments.	Feasibility Study SOLIDWORKS	Following the study's methodology will bring optimal results for simulating the implementation of an SWT. Results indicate that the spot that will provide the best energy production outcome is located on the building's rooftop.
Zanforlin and Letizia 2015	Analyze the performance of a vertical axis wind turbine (Darrieus turbine) after being mounted horizontally on a gable roof and a diffuser wall.	CFD Study ANSYS Fluent	By coupling a two sloped rooftop and a wall that has a convergent-divergent shape, the power output of the turbine increases by 40%-50%. If the diffuser wall is not part of the structure, then the turbine needs to be placed at a higher altitude. The wall's unique shape aids in increasing speed velocity or directing wind to a proper angle, when wind direction is downstream or upstream respectively.
Emejeamara and Tomlin 2020	Create a methodology to assess a small wind turbine's power performance in a turbulent urban environment, since the power assessment before implementing a small wind turbine is done in mean windspeeds and not in turbulent winds.	Numerical Simulation MATLAB	The study adds turbulence, inertia, and turbulence response as factors in a methodology to predict the power generation of a Darrieus type VAWT. Without these factors, performance indicators end up being misleading in real conditions. The method implemented a calculation that would "multiplying the CTC value with the wind energy available to the turbine system for a given burst period." CTC value being the newly introduced parameter: turbulence induced performance coefficient (CTC)

Table 10 Table 8 continued

Main 2013	Analyze the potential of wind power production.	Feasibility Study EXCEL	Annual electricity production is calculated at 23163.85kWh/year, 1,84% of the building's annual electricity demand. The payback period of the investment is at 18,31 years. To shorten the payback period; a green certificate shortens the reimbursement period by 3,7 years. The Proposed mounted turbine is feasible and financially viable if the incentives given are in place.

3.4.2 Noise Production of Small Wind Turbines

Sound assessment is performed on small and regular turbines since they tend to produce noise due to constant movement. Research focuses on identifying the optimal position for the turbine to minimize sound pollution production (Table 11 and Table 12).

Table 11 Scientific papers for SWT noise generation

Author(s) & Year	**Purpose**	**Method & Tool**	**Results**
Van Overeem et al. 2017	The paper is a study that investigates the positioning of SWTs in an urban context, more specifically, on the noise barriers of highways.	Numerical Simulation ANSYS ICEM	To conclude, regarding SWTs, high-rise buildings are the best case for building integrated wind harvesting; however, SWT implementation can cause vertex shedding. Therefore, simulations need to be conducted at all stages of planning for new and existing buildings. That way, vertex shedding can be avoided. A complementary way to avoid vibrations is by checking turbine blade angles

Table 12 Table 11 continued

Author(s) & Year	Purpose	Method & Tool	Results
Botha et al. 2016	The conference paper is studying three different blade designs and the sound emissions they can produce.	Numerical Simulation BEM QBLADE CFD	The paper considers two diverse types of noise (inflow & self-generated noise). Results show that the primary source of noise produced by the blades is inflow noise.
Hodgson n.d.	The project aims to inform the public on noise emissions of small wind turbines through research, surveys, and experiments.	Comparative Analysis Statistical Software	The longer the distance of the source to the receiver, the lesser the sound pollution. The study sets maximum regulatory measurements for placing an SWT
Hashem et al. 2017	The paper studies noise emissions from the Wind-Lens type of small wind turbines.	Numerical Simulation ANSYS Fluent	The diffuser wind turbine (Wind-Lens) was compared with a bare wind turbine, and the latter was found to produce less noise. Different shapes of the diffuser were studied and the
Dahirul et al. 2020	The paper investigates the noise pollution of a small wind turbine according to the US's standards by the American Wind Energy Association and the IEC 61400-11.	Statistical Analysis	When studying the noise generated by a turbine, more than one distance needs to be considered. The effect that noise has on the urban environment is not undervalued.

Moreover, because domestic use turbines are placed in places where people live and react daily, sound assessment and improvement of the noise that SWTs produce is essential.

3.4.3 Positioning of Small Wind Turbines

The position of a turbine is critical for the efficiency of the device. Research on locating SWTs is vital because engineers can have previous knowledge of which place is adequate and avoid planning errors. Studies on setting SWTs include studying the direction of the incident wind (Table 13). Moreover, the surrounding environment, for example, whether the turbine will be placed in a dense area or not (Table 14). Turbulent flows that are analysed make the positioning of the turbine safer (Table 15).

Table 13 Scientific papers for SWT position

Author(s) & Year	**Purpose**	**Method & Tool**	**Results**
Yang et al. 2016	The paper studies two perpendicular buildings and for what level of performance they could provide. A variety of sizes and heights are put under different input variables in CFD simulations to show wind harvesting potential.	Numerical simulations ANSYS Fluent	A wind direction provides optimal results mostly when it hits the building at a 45-degree angle. The most significant wind energy harvesting potential is over the roof. The total land coverage of a building is pivotal for wind harvesting.
Wang et al. 2018	The paper investigates the optimum height and position of roof-mounted wind turbines through CFD simulations. The research results act as a suggestive method of selecting the appropriate type and position of the SWT.	Numerical Simulation ANSYS Fluent	Evaluating how strong turbulence is and the wind accelerating factor by considering the yearly wind speed average, the study presents a method for micro siting through CFD simulations. The proposed installation height is at 1,30-1,50 times the total height The recommended position is the edges of the rooftop

Table 14 Table 13 continued

Author(s) & Year	Purpose	Method & Tool	Results
Abohela et al. 2013	The paper demonstrates the urban environment and the different building shapes and heights as a means of support to wind streams on UWTs; to eliminate the public misconception that UWTs are not a feasible solution for on-point power production in cities.	Comparative Study ANSYS Fluent	The research outcome is that the best location for a wind turbine to perform is roof-mounted, mostly on high-rise buildings. The higher the building, the less the Windstream on the roof is affected. In cities, the surrounding environment of a building is affecting the turbulence. Other factors influence turbulence, such as the height, a prominent factor when the surrounding buildings' effect is not there anymore.
Toja-Silva et al. 2015	As the century's trend is to exploit energy from natural resources, the article studies the morphology of roofs in high-rise buildings for SWT implementation. Several various aspects are considered. More specifically, wind flow surrounding a building, the roof's shape, and the effect of its edges.	Comparative Study	What mainly influences wind turbulence on the roof is the passage from wall to roof. The article suggests that more investigations regarding vaulted and spherical roofs should take place in the future.
Ciobanu et al. 2019	This paper determines the circumstances that influence the positioning of an SWT. Numerical simulations are made in order to locate the optimum spot for placing an SWT.	Numerical Analysis ANSYS Fluent	Shape influences turbulence occurrence. SWTs can be installed on any type and shape of building, as long as nominal power location is taken into consideration For the sides of the buildings, the best type of SWTs is vertical. Wind potential and building design are essential to efficiently harvesting wind

Table 15 Table 13 continued

Author(s) & Year	**Purpose**	**Method & Tool**	**Results**
Rahman Elbakheit 2013	The Paper studies the aerodynamic performance of high-rise buildings regarding static design and wind turbine integration	Comparative Study	To conclude, regarding SWTs, high-rise buildings are the best case for building integrated wind harvesting. However, SWT implementation can cause vertex shedding. Therefore, simulations need to be conducted at all stages of planning for new and existing buildings. That way, vertex shedding can be avoided. A complementary way to avoid vibrations is by checking turbine blade angles and the supporting tower's symmetrical cross section.
Zabarjad Shiraz et al. 2020	Present a methodology for wind pattern investigation in urban environments.	Numerical Simulation ANSYS Fluent	Energy production is affected by the morphology of the site. High Building Density sites are not recommended as the potential for energy production is exceptionally low.

3.4.4 Financial Aspects of Small Wind Turbines

Investing in domestic use turbines is vital in deciding whether one should proceed with acquiring the technology. Research on the topic still lacks, as experts focus more on the technology and the energy it can produce rather than the investment (Table 16 and Table 17).

Table 16 Scientific papers for SWT turnout

Author(s) & Year	**Purpose**	**Method & Tool**	**Results**
Ghaith et al. 2017	The article studies the economic factors of offshore as well as onshore wind energy in Europe. To determine the economic gain of wind energy with the collaboration of manufacturers and developers, the factors that influence them are studied.	Review and Statistical Analysis	The cost of producing a wind turbine is very influential to the overall investment. Research should focus on size and materials. Policies influence the return on investment.

Table 17 Table 16 continued

Author(s) & Year	**Purpose**	**Method & Tool**	**Results**
Kabir et al. 2012	The paper studies the life cycle assessment of wind turbines and how energy-intensive they are. It also compares three different arrangements of small wind turbines that would ultimately produce 100kw of power and compare those installations' economic benefits.	Life Cycle Assessment	From a financial point of view, a small wind turbine does not benefit the investor. The most emission inducive processes are production, transportation, and installation.
Charabi and Abdul-Wahab 2020	The study illustrates the possibilities for wind generation in Oman and the most financially viable choice of small wind turbines.	Performance Analysis Homer Software	The most economically efficient turbine is the one with the highest power output. However, lower power output can be beneficial to smaller wind power plants and lower maintenance costs. Specifications play a significant role in payback since if the cut-in wind speed is low, the turbine can start producing in lower windspeed areas. A substantial reduction of carbon emissions can occur in wind turbines located in southern areas.

3.4.5 Case Studies on State of The Art

Case studies showcase the implemented examples of the technology and are a good source of information regarding failures and positive aspects of small wind turbines. For the literature review of case studies, the studies of the examples presented in chapter 3.3 are reviewed (Table 18 and Table 19).

Table 18 Scientific papers for state of the art examples

Author(s) & Year	**Case**	**Purpose**	**Method & Tool**	**Results**
Kompatscher 2015	Strata Tower London fail	This Master thesis aims to investigate the reasons why Strata Tower's Building Augmented Wind Turbines failed to function as expected- through CFD simulations. Moreover, it shows ways to optimize wind turbines through building design reform.	Numerical study for Case Study	Results consider the amplification factor of the wind distribution as the point of reference to specify whether wind distribution is affected by the opening's morphology.
Dymock 2013	Strata tower London	This dissertation is a comparative study between the strata tower and the London South Bank University.	Comparative analysis	The study presents results on atmospheric, vibrations, noise, and annual energy yield performance. The study aims to define urban wind turbine use by studying two cases—one of a roof-mounted turbine and a building-integrated turbine.
Saeed 2017	Bahrain World Trade Center	The article shows the applicability of wind turbines on buildings, taking as an example the World Trade Center in Bahrain.	Technical Review	The building's wind turbine implementation was a successful one. The CFD simulations do not illustrate the actual performance in real conditions, but they are valuable to the designing process. From a design perspective, the way the building is displayed gives a sensation of flying.

Table 19 Table 18 continued

Author(s) & Year	Case	Purpose	Method & Tool	Results
Li et al. 2016	Pearl River Tower	The study is assessing the performance of wind turbine implementation on high-rise buildings.	Comparative analysis	The study considers weather data from the area where the building is located; to perform wind tunnel tests. Building surface, shape, and height influence amplification effects of wind speed. Urban surroundings interfere with wind patterns. Wind turbines located on higher levels have better annual yield than those located in lower levels of the building.
Bobrova 2015	Project WEB Strata Tower Pearl Tower	The paper is describing the architectural shaping of structures when integrating small wind turbines.	Technical review	The design process of implementing small wind turbines should be handled in a careful manner, not only in terms of shape but also safety.

3.5 Return on Investment Estimation

One of the positive aspects of implementing renewables in cities is the beneficial pay-off rate. To illustrate the return on investment, three turbines from the tables in chapter 3.2.7 were selected and compared to the current electricity prices in Europe (2019 data). The turbines were selected according to data availability.

The following companies produce the three reviewed turbines:

- Kliux
- Halo
- Vision

The initial datasets were:

1. Maintenance Cost (EURO/year) (M): All costs involved in any yearly maintenance or upkeep of the wind turbine and disposal.
2. Expected Lifetime, in years (L): An estimate of how long a wind turbine will last before it no longer produces energy.

3. Installation Cost (EURO) (I): All costs involved in securing the wind turbine and pole onto the roof.
4. Supervision Cost (EURO) (S): The cost of a professional technician supervising the turbine during the year.
5. Turbine Cost (EURO) (C): The cost of the wind turbine.
6. Electricity Cost (EURO/kWh) (E): Cost the user pays to their electric utility provider for each kilowatt-hour.
7. Electricity Produced (kWh/year) (P): The number of kilowatt-hours the wind turbine is estimated to produce.
8. EU Electricity Prices: The prices of electricity in EU countries, including tax.

In order to produce results that will show the financial benefit of the investment, two calculations are performed. First, is the cost per total electricity output and second the variance of the cost/energy deducted by the electricity prices of EU countries.

A. Cost Calculation:

- Total cost per year is calculated by adding data 1-5: Total Cost= M+L+I+S+C
- Energy Output per windspeed is derived from the annual power output diagram (see diagram in Appendix A, p.84).
- Calculation of the end price for electricity produced by the turbine.
  Cost/kWh= Total cost/ Energy Output.

B. Variance Cost per Country:

- Variance is calculated by deducting the country’s electricity per hour price (without taxes) from the end price of electricity produced by the wind turbine. The results of the calculations can be found in the Appendix B (p.87) in the tables section.
  Variance= (cost/kWh) - (electricity price)

Finally, the Return on Investment (ROI) was studied over a period of 20 years. Results are illustrated in the graphs that follow (Figure 19, Figure 20, Figure 21) and are compared with results from studies on return on investment in chapter 4.

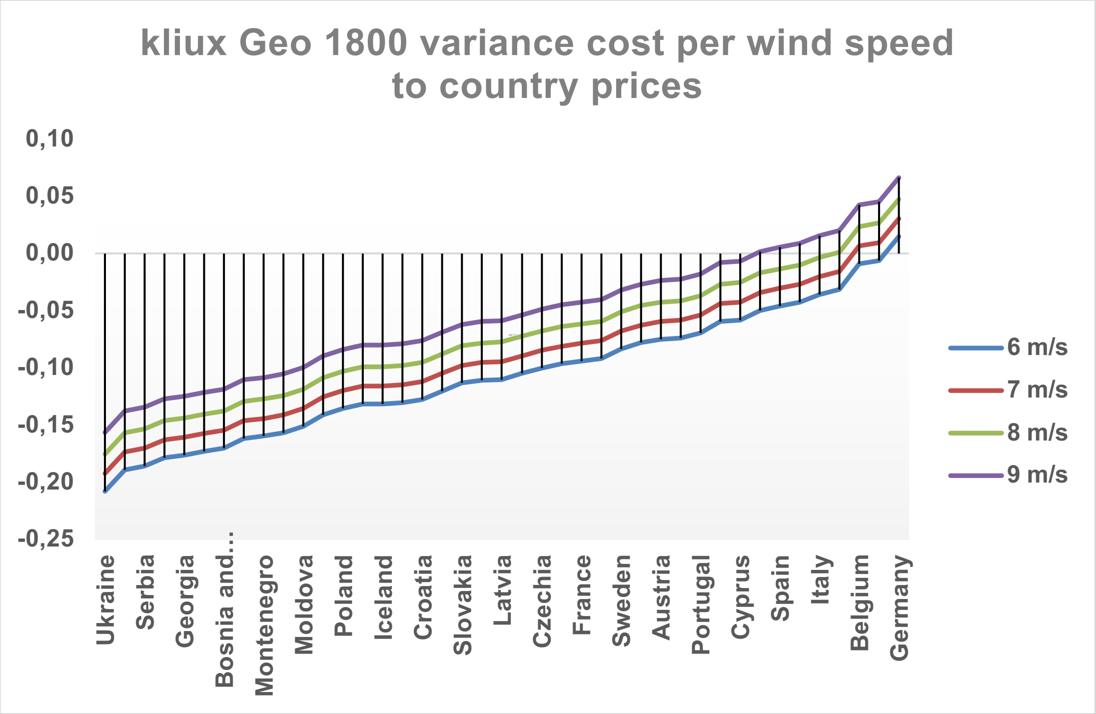


Figure 19 Kliux Investment Benefit per country; showcasing the variance to electricity price in euros per country and windspeed

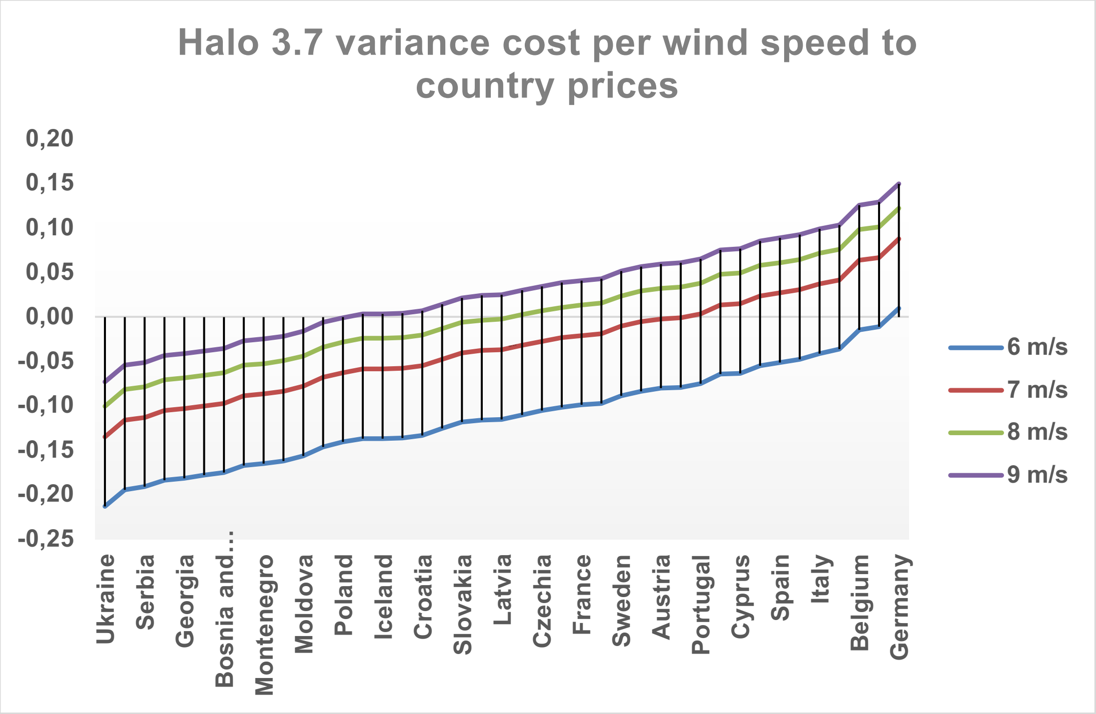


Figure 20 Halo Wind Turbine Investment Benefit per country

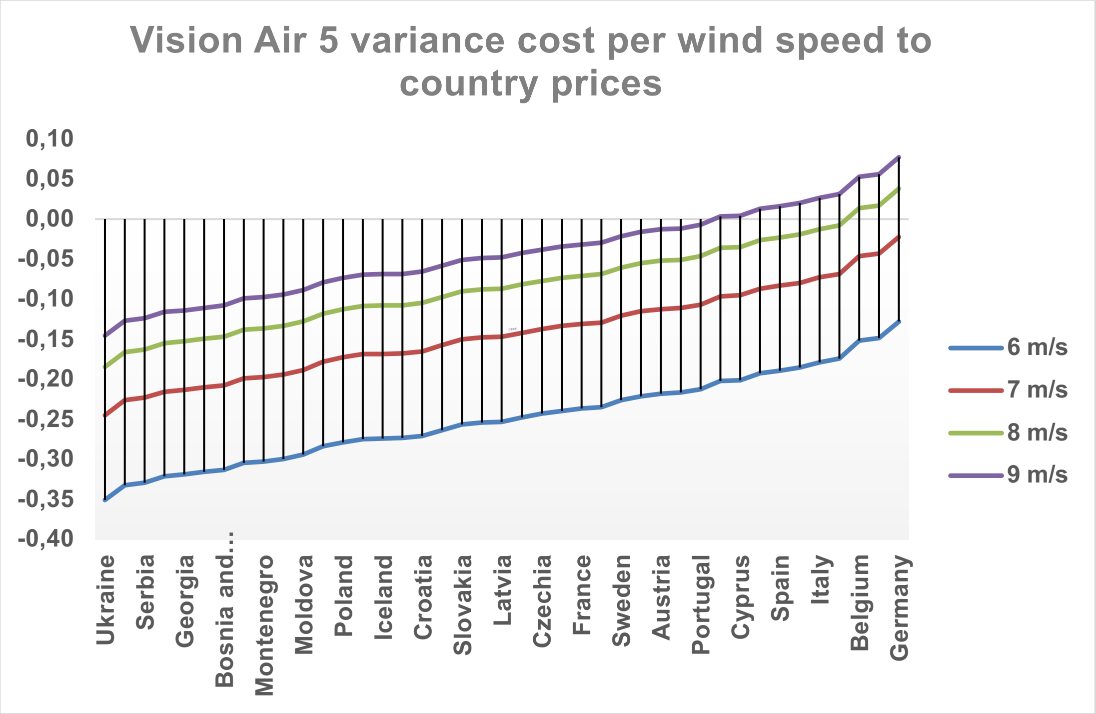


Figure 21 Vision Air Wind Turbine Investment Benefit per country

3.6 Estimation of Wind Energy Generation for Vienna

The city of Vienna is working on actions to improve its greenhouse gas emissions by implementing strategies that impose renewable energy sources. Renewable energy implementation is essential because Vienna's building sector is consuming 1/3 of the total energy consumption (City of Vienna 2018).

Despite wind conditions being moderate in Vienna, the implementation of small wind turbines could be inefficient, because the turbine would spend many days without functioning (when winds are below the cut-in windspeed). Using the formula for rated power (see section 3.2.1 above), the results for rated power in different windspeeds (2,3,4 and 5m/s) and with a wind density of 1,225 kg/m^3 (Kaufmann and Tran 2015) and a maximum power coefficient of 0,59 (RWE npower renewables 2007) are calculated as illustrated in the table below Table 20.

For the power calculation to be more accurate, the wind capacity factor should be considered; an average capacity factor for the EU of 21% is used (Boccard 2008). The results of the rated power calculation are multiplied by the same factor.

Table 20 Rated Power of HALO6 wind turbine at different wind speeds

Windspeed (m/s)	**Rated Power (W)**	**Rated Power with Capacity Factor C_p (W)**
2	13,01	2,70
3	44,01	9,20
4	104,32	21,88
5	203,75	42,79

The rooftop capacity of flat roofs in Vienna is considered the same as for planted roofs since they also require an inclination smaller than 5 degrees. Therefore, according to a study for planted rooftops in the city of Vienna (Figure 22), the percentage of potential rooftops is calculated at 20% of the existing buildings (rooftop inclination between 0 and 5 degrees) (Dang et al. 2019).

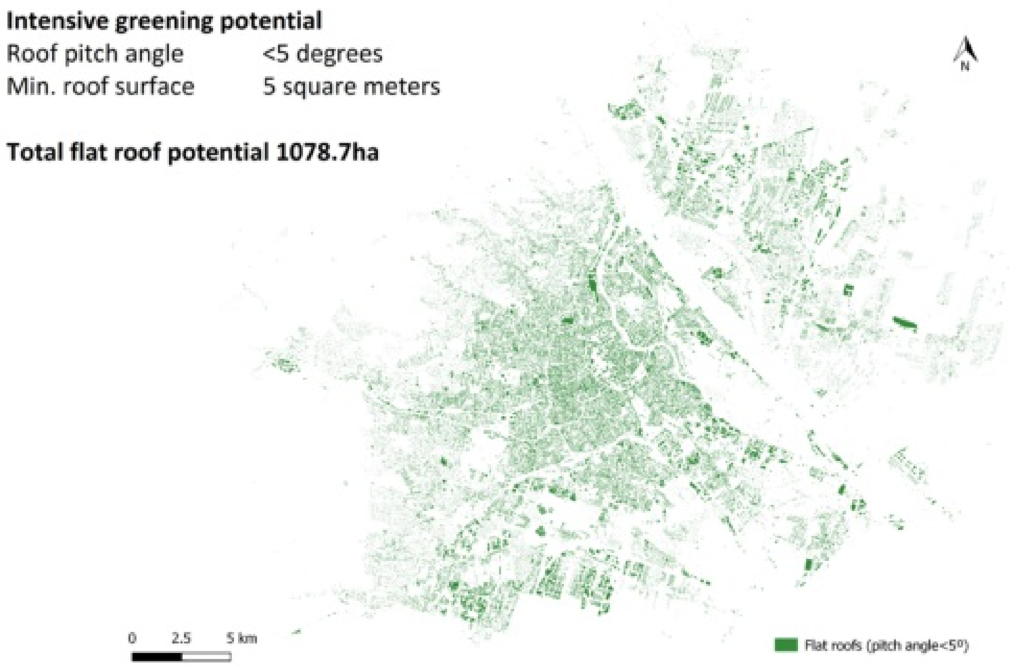


Figure 22 Flat roof potential; Identified flat roofs in Vienna using ARCGIS (Source: Dang et al. 2019)

Furthermore, the gross electricity consumption of Vienna as calculated by the Austrian statistic agency is 3.654 GWh (Statistik Austria 2018), and the number of buildings in the city is approximately 165000 (City of Vienna 2018). The graphic representation (with information about the energy consumption of the city) of Vienna's energy flows can be found in the table in Appendix A (p.87-83).

With the aforementioned factors in consideration, the potential electricity production, the city's annual demand coverage, the total wind turbines installed, and the investment cost from a small wind turbine are illustrated in the following table (Table 21). HALO produces the chosen turbine and its characteristics are showcased in Table 4. The turbine is selected because it has a small swept area and therefore more turbines can be installed on one flat roof. Moreover, it has a high rated power and annual energy output because it is a shrouded turbine. Shrouded turbines accelerate wind velocity and, therefore, can produce more power.

The process for estimating Vienna's potential is:

1. Selection of small wind turbine according to previous cost estimation for electricity production: Selected turbine HALO 6kW.
2. Find the percentage of flat roofs in Vienna: 20% according to data from the previous study about green roofs.
3. Estimate the number of useful flat roofs: Estimation to 1/3 of the flat roofed buildings (considering they have appropriate height and wind conditions)
4. Find volume of available surface: The roof surface of Vienna is considered to be 53 km^2 (Wiener Solar-Potenzial 2020). Out of that, average surface of building rooftop is calculated to be 321 m^2.
5. Derive data for annual electricity consumption of Vienna from Statistik.at: 3.654 GWh.

   Annual electricity consumption of Vienna can be found in Appendix A, p.84-83.
6. Estimate yearly energy output for the HALO turbine from the manufacturers' data.

   Find surface needed for the turbine according to manufacturer (see Appendix A p.84): 10 m^2 (estimation for more space around the turbine +5m^2, to allow movement around it).

   Find weight of the turbine to calculate the added weight on each building. Weight of one turbine: 375 KG (see information in Appendix A p.82)
7. Results for: Number of SWTs per building, Used space on the rooftop in m^2, Added weight from the turbines, Total annual output in MWh, Percentage coverage of annual demand, Total number of wind turbines, Total investment in million Euros.

The results are showcased in the table below (Table 21).

Table 21 Calculation results of wind turbine potential for the city of Vienna

Number of Wind Turbines per Building	Used sq. Meters of Each Roof	Added Weight per Building in Tons	Total Annual Output MWh	Pct Coverage of Annual Demand	Total Number of Wind Turbines
3	45	1,13	231.000	6,32%	33.000
6	90	2,25	462.000	12,64%	66.000
9	135	3,38	693.000	18,97%	99.000
12	180	4,50	924.000	25,29%	132.000
15	225	5,63	1.155.000	31,61%	165.000
18	270	6,75	1.386.000	37,93%	198.000
21	315	7,88	1.617.000	44,25%	231.000

Further analysis of the results will be discussed in the discussion and conclusions chapters.

4 DISCUSSION

In this chapter, the data presented in chapter 3 will be discussed. In addition, results between findings in the literature review as well as the calculations and collected data will be compared.

4.1 Comparison of Literature Review Findings to Estimation Results

In section 3, the overview of research on Small Wind Turbines showed that what constitutes the use of SWTs as necessary and how much energy they can produce to substitute traditional non-sustainable sources of energy. Maximum efficiency can be achieved in various ways; by changing the design, installing the turbine in a specific spot for maximum wind harvesting, or changing the number of blades. Research that is being done is in order to prove the viability of the application of SWTs.

Furthermore, research that focuses on changing the blades' design for the annual energy production to increase is one of the most dominant in the scientific community. For example, nose and nacelle design affect the annual yield. In a study (Wang et al. 2008) performed on domestic use turbines, the tested turbine started to have a higher performance at a wind speed of 6,5 m/s, a relatively high speed for an urban area. Over the scope of a year, the turbine could produce 872 kwh, an energy production better than other SWTs. However, the result of 872 kwh per year did not reach the expectations of covering the building’s energy consumption; therefore, the paper suggests further studying the issue alongside the response to sudden changes in wind patterns (Wang et al. 2008).

Moreover, urban conditions affect energy production as cities tend to have lower windspeeds than the traditional wind farm locations for regular-sized wind turbines. Hence, research on the small wind turbine design focuses on optimizing the turbine’s starting windspeeds (cut-in wind speed). Moreover, turbulent flows -that can be damaging to the turbine- in cities are due to buildings' existence; therefore, placing the turbine in a position not affected by turbulent flows is important. Overall, to find the best solution for design and position, research focuses on simulating the behavior of the turbine before implementing it with the help of Computational Fluid Dynamics.

The following chapters provide an analysis and comparison of the reviewed papers. Moreover, the second part of the chapter is dedicated to examples of building projects that implemented SWTs in their design.

4.1.1 Requirements for Cut-in Windspeed

The lowest wind speed required for an SWT to start rotating is as low as 1,6 m/s (Figure 23). However, it is not the most common speed as it is deficient, and most turbines are produced to start with a slightly higher speed. In his paper, Main (2013) analyzes wind power production's potential by standing the starting wind speed and the annual energy production. The research method includes an implemented SWT and studies its behavior under a mean wind speed. What this has as an outcome, is that simulations are not realistic at the end since wind speed changes continuously. However, according to the study, the site chosen for research for SWT implementation is classified as a moderate windspeed class, which gives the researcher the freedom to use a mean wind speed in simulations. This outcome shows the importance of starting wind speed and its relation to wind conditions.

As observed in the table below (Figure 23), most SWTs require a relatively low wind speed to start. However, only 11% of them manage to start in substantially low wind speed, between 1,6 and 2,0 m/s. In Main's (2013) study mentioned above, a turbine's (cut-in speed 2,5 m/s; mean wind speed 4,91 m/s) annual electricity is calculated at 23163.85kWh/year, 1,84% of the annual electricity demand of the building (Main 2013). In that case, if the turbine started at a windspeed lower than 2,5, it would have the capacity to produce more electricity and raise the percentage of covering the annual electricity demands. Therefore, the low availability of turbines with a low cut-in wind speed is not fruitful, and manufacturers should pay more attention to producing turbines that start with low speeds.

Moreover, another aspect that is influenced by wind speeds is the tip speed ratio, which also correlates to power production (ElCheikh et al. 2018). The tip speed ratio is the tangential speed ratio on the blade's tip to the actual wind speed (REUK 2020). Therefore, the cut-in wind speed- that initiates the turbine blade to move and obtain a tangential speed- is influential to the blade tip's tangential speed and to harvesting air.

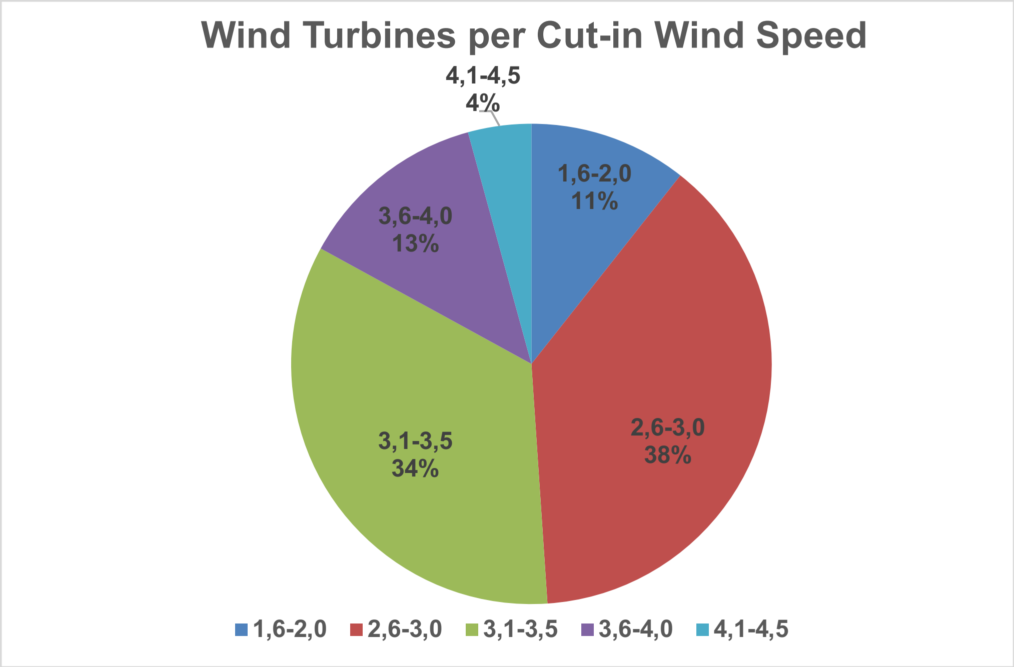


Figure 23 Table of Small Wind Turbine requirements for starting wind speed

Simulating the performance before installing a turbine is essential; however, considering more aspects can lead to more accurate results. A more in-depth analysis is to include site and building assessment. A feasibility study made in a suburban area of Mexico City (average wind speed in the area 5,83 m/s) identifies efficiency through CFD simulations. Under these conditions, the proposed course of action can produce 60000kwh per year, covering the building's demand (Arteaga-López et al. 2019). As referred to in section 3.1, manufacturers offer an on-site assessment, but what constitutes an assessment as efficient is the CFD simulations. They provide information not only for the behavior of the turbine under a certain windspeed, but also for the influence of the surroundings.

4.1.2 Position of Small Wind Turbines and Their Prerequisites

Placing a small wind turbine involves innovative research on methodologies that are combining Computational Fluid dynamics with meteorological data. Studying the ground formation and correlating it to weather patterns proves that energy production is affected by the site's morphology. Moreover, implementation of SWTs in High Building Density sites is not recommended as energy production's potential is meager, even when the turbine is placed at a higher altitude. Therefore, a recommended area to use SWTs is at Low Building Density Areas, where the wind patterns are less affected (Zabarjad Shiraz et al. 2020).

The installation of small-scale wind turbines in a specific location has a range of preconditions. Sarkar (2012), in his paper for Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy, states that the placement of the turbines is depended on the following factors:

"1) Wind speed: The power available from the wind is a function of the cube of the wind speed. Therefore, if the wind blows at twice the speed, its energy content will increase eight-fold. Turbines at a site where the wind speed averages 8 m/s produce around 75-100% more electricity than those where the average wind speed is 6 m/s.

2) Wind turbine availability: This is the capability to operate when the wind is blowing, i.e. when the wind turbine is not undergoing maintenance. This is typically 98% or above for modern European machines.

3) The way wind turbines are arranged: Wind farms are laid out so that one turbine does not take the wind away from another. However other factors such as environmental considerations, visibility and grid connection requirements often take precedence over the optimum wind capture layout." (Sarkar et al. 2012a, p.1)

Observing the surrounding area means identifying any objects that can alter a homogeneous flow, e.g. trees, buildings, or walls. Moreover, the orientation of the walls can lead to diverse wind behavior. Buildings facing north are the best for wind harvest. Modeling the building under various physical settings can indicate which walls have a wake effect (wake effect is the effect behind a turbine, where the wind is slowed down and turbulent) (Arteaga-López et al. 2019). Hence, identifying which spots on the roof are not suitable for installing an SWT and at which height the wake effect will not influence the performance is essential.

As mentioned above, the orientation of the building influences the positioning of the turbine. However, it is not just orientation that is important, but also the shape of the building. For example, on a building of a curved shape, turbulences occur on the building's side and top (Ciobanu et al. 2019). Therefore, a recommended spot for positioning an SWT is 7-9m above the rooftop level (Ciobanu et al. 2019). On the other hand, if the building's shape is parallel, it endures turbulences on the corners and the top. In this case, the recommended spot for, preferably a Vertical Axis SWT, is at a 9-10m above rooftop level (Ciobanu et al. 2019).

Moreover, for more complex shapes (a combination of triangles and rectangles), the proposed location for SWTs is the building’s upper terrace, and the proposed SWT type is again a vertical axis wind turbine (Ciobanu et al. 2019). Location for implementing SWTs depends on how the shape of the building affects the wind flow. Generally, the optimal positions are above rooftop level, where the peak intensity of turbulences occurs. Therefore, SWTs should be placed on towers that extend above the prementioned level.

Regarding the influence of the building's shape; the buildings with vertical sidewalls create turbulences at the edges, whereas oblique sidewalls create turbulences inside the structure. Overall, the best spot for SWTs is the building's rooftop than the sides (Ciobanu et al. 2019).

To further illustrate the benefit of implementing SWTs on rooftops, Figure 24 showcases the amount of turbines that would need to be installed in the city of Vienna and the electricity that they would cover. Installing small wind turbines on the flat roofs can cover half of the city’s electricity demand. More specifically, in the estimation for the city of Vienna in section 3.6 above, the selected wind turbine could cover up to 50% of the city’s electricity demand (Table 21 *Calculation results of wind turbine potential for the city of Vienna*). Moreover, the electricity demand and the percentage coverage of installed wind turbines per flat roof is proportional to the annual output. That is a reasonable outcome, as more wind turbines would produce more energy and therefore cover more of the demand.

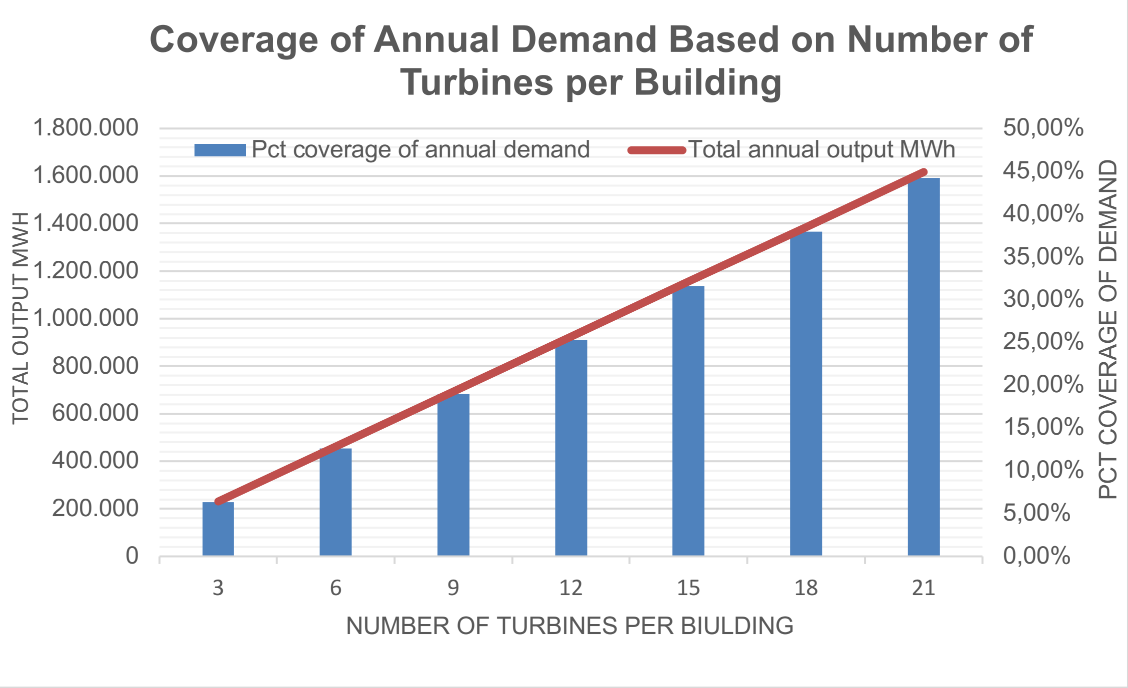


Figure 24 Resulting graph from Table 19; Coverage of annual electricity consumption by number of turbines per building

However, the benefit of covering the city's power consumption comes with a price. When installing an SWT, considering just the performance it will have on a specific spot is not enough. Turbines are an installation that has a specific weight that lies on the structure; hence statics of the building is altered. In Table 21 on page 52 showcasing the implementation of SWTs on Vienna's flat roofs; the added weight per building would be up to 7,8 tons- a weight that an old structure would barely tolerate. Moreover, SWTs function at all hours, which indicates constant movement happening on the skeleton of the building. In addition, the continuous movement is also emitting sound, which can be bothersome for the building's tenants.

Sound assessment is conducted to find the best distance between the turbines, in order to avoid sound pollution. The most dominant source of noise production on a turbine is inflow wind. That happens because the turbine is placed in an environment of turbulent flows. Hence the blades have incoming turbulent wind, which makes them more sound-emitting. Therefore, SWTs noise production is connected with location (Botha et al. 2016).

Moreover, for SWTs placed in the lower levels of the city (e.g. streets and parks) the same sound emission rules as to when they are on buildings are imposed. An exciting idea is to implement SWTs on highways and take advantage of the wind flow generated by cars that pass by. In such cases, the highway's noise needs to be considered as well (Van Overeem et al. 2017). The sound assessment considers both sound intensity from the SWT and the highway. The minimum distance that SWTs should be placed according to each country's law (Van Overeem et al. 2017). Usually, the requirements of a minimum distance between a building and a noise-producing source should be 40m (Van Overeem et al. 2017). Therefore, considering that there are two sources of noise when turbines are installed on highways, the distance increases substantially, and some areas may not accommodate such installations.

In addition to sound emissions, urban integrated wind turbines cause vibrations, especially to a structure (building-integrated wind turbines). More specifically, each part of the turbine can cause different vibrations; for example, blades with different pitch angles cause vibrations inside the turbine, especially in higher wind speeds (Rahman Elbakheit 2013). Contrary to sound assessment, which investigates the distance between each turbine, vibrations assessment focuses on each turbine. A proposed way of avoiding vibrations by Elbakheit (2013) is to study the turbine blade angles in relation to the SWT tower that holds the rotor.

As an alternative to SWT towers (where a turbine is usually placed), high-rise buildings can function as towers. In his paper, Rahman Elbakheit (2013) is considering placing the turbine directly on the rooftop level (for HAWT) or the sides (for VAWT) in order to reduce the effect of vibrations. He proposes using simulation to identify the exact spot where vibrations occur on a turbine. Proposed areas for implementing SWTs is the top or the sides of the building (Inield 2012). The main concern is for existing buildings, because they were not designed to withhold an SWT. The integration of SWTs can cause vertex shedding effect (a phenomenon that causes oscillations and vibrations on the construction) since the building's aerodynamic wind pattern will change. For that reason, in cases of existing buildings, the paper suggests using VAWT, which is quieter and less prone to vibrations (Rahman Elbakheit 2013).

To conclude, regarding SWT placing, high-rise buildings are the best case for building integrated wind harvesting. Nonetheless, the total aerodynamic behavior is the leading cause of air movement (Rahman Elbakheit 2013). Therefore, simulations need to be executed at all stages of planning for new and existing buildings. That way, turbulence and vertex shedding can be avoided. Moreover, when planning to implement turbines in new constructions, the building's shape needs to be considered. Furthermore, when installing turbines on existing structures, the position and turbulence caused by the turbine should be examined.

4.1.3 Design and Performance of Small Wind Turbines

Having a proper design of the turbine components can be as effective as positioning an SWT correctly to achieve optimal performance. Design encompasses the correct placement of gear as well as giving the turbine an appropriate shape. The blade shape and the blade number play an essential role in the energy that the turbine will produce. Moreover, the rotor, which is the energy generation source, connects all the components that constitute a turbine and needs an efficient housing design. Turbines that are well designed perform better and can handle various climatic conditions.

A factor that influences the climate adaptability of a small wind turbine is the number of blades. Hence, there exists a variety of small wind turbines that are offering various numbers of blades; turbines with two blades as well as with three are available in the market. What constitutes the number of blades as influential is that the swept area changes and alters the performance. Moreover, it is the sum of the blades that can alter wind harvesting and the structure of the blade itself.

To analyze how the behavior of an SWT changes with various number of blades, one can consider the study of ElCheikh et.al (2018), who tested the performance of an orthotope vertical axis wind turbine by changing the number of blades as well as the thickness. He argues that a higher solidity helps boost the power coefficient, hence produce more energy. The aforementioned argument refers to overall solidity, which can change either by increasing or decreasing the blade height ratio (aspect ratio) to the cord or the number of blades. However, when considering the aspect ratio, the change in the number of blades can have negative results. In other words, if the same number of blades is preserved, and only the aspect ratio increases, then the power coefficient decreases (ElCheikh et al*.* 2018).

In addition, studies made on other types of vertical axis turbines produce similar results to ElCheikh’s research. More specifically, according to Rezaeiha et al. (2018) and their paper on *optimal aerodynamic design of vertical axis wind turbines,* the conclusions are:

- Optimal tip speed ratio and the number of blades are independent of the turbine’s power coefficient (when tested at the constant Reynolds number chord-based Airfoil conditions).
- When tested at a given solidity, then the number of blades influence the power coefficient.
- Angle and velocity are also independent of the number of blades.
- A lower number of blades increases the reduced frequency, hence the lift, and lowers the drag.

ELCheikh (2018) and Rezaeiha (2018) argued that solidity and the number of blades change the way a turbine functions and that by altering only these factors, the power produced will be higher. However, there is also the notion that the rotor can influence the turbine's behavior without altering the blade count. Rotor plays a vital role because revolutions per minute (rpm) can improve the need for cut-in windspeed, making the turbine operative in dense areas where the wind does not reach high velocities.

Furthermore, a rotor house (the surface that covers the rotor) is an aspect that affects performance. In a vertical axis turbine, a rotor house can be covering the blades to create a current, hence more whirl on the blades that can produce more energy. Manganhar (2019) studied a three-bladed Savonious turbine rotor in two different states regarding rotor house (RH). The two states included a rotor house and the lack of it, and results showed that the rotor house state performed better (Manganhar et al. 2019). More specifically:

1. Performance of the two states at zero angle of incidence: A rotor with RH can start at lower wind speeds than without and produce more rpm with the velocity change. Therefore, it improves the cut-in speed requirement. Rotors with RH have a higher performance coefficient than those without. Observations show that the power coefficient decreases as wind velocity increases. High-speed flows will generate more turbulence to the system because the rotor house helps the wind flow to accelerate when entering the RH and decelerate when exiting, resulting in blockage effects. Therefore, the performance at higher windspeeds is compromised.
2. Performance of the two states at different angles of incident: The reason for inputting different incidence angles was to investigate their effect on the performance. The rotor with RH performed well under various incident angles and windspeed.
3. The rotor's field testing with and without RH: At wind velocities varying between 2,1-5,5 m/s the rotor without Rh produces 60-350rpm, whereas with RH 100-400rpm, therefore a rotor with RH has a better performance.

A rotor with RH performs better and improves efficiency to more than double the bare rotor. Moreover, in real environmental conditions, turbulent flows decrease the turbine's performance (Manganhar et al. 2019). The rotor's significant role is also projected in the diameter, where manufacturers focus on providing a small size rotor.

In addition, the rotor diameter can change the wind harvest potential. A larger diameter has a bigger surface and can harvest more air (Rezaeiha et al. 2018). However, in a city, a turbine that occupies a big surface is not preferred. The table below illustrates that rotor diameter varies between 1 and 21 meters; in addition, most rotors are between the scale of 2-5 meters (Figure 25). That is because there is a need to maintain small size in order for the turbine to be versatile and easily placeable in various places.

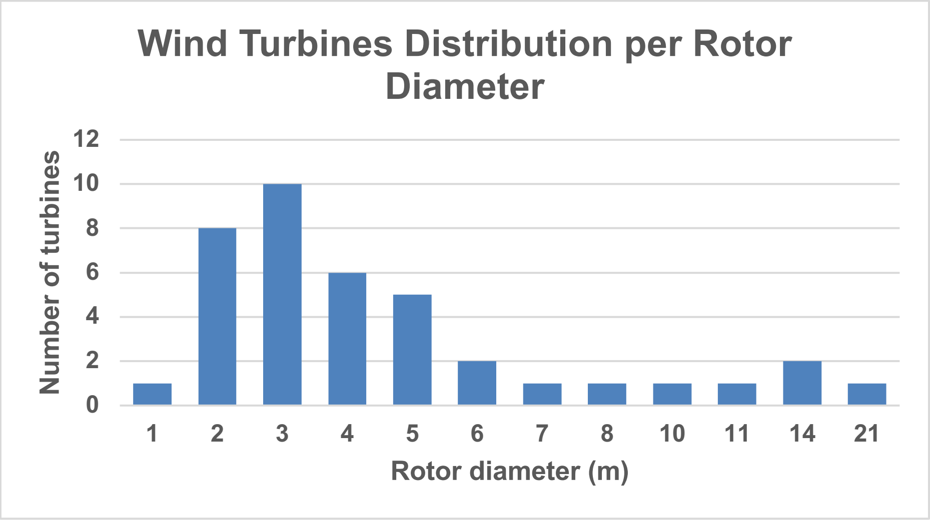


Figure 25 Rotor Diameter Size

On the other hand, the rotor is not the only component of turbines that relates functionality to efficiency, but the blades attached to it affect the turbine's performance. What is influenced mostly by blade design is the tip speed ratio, which determines how much power the rotor will take. A poor blade design can result in either too low or too high tip speed ratio, both of which are detrimental to the turbine's performance. However, even though the number of blades affects functionality overall, the blade count does not affect the optimal tip speed ratio reduction and different turbulence intensities (Rezaeiha et al. 2018).

Moreover, while the number of blades affects the performance, it is not the only aspect of the blades that can improve performance. In addition to blade count, blade design is also crucial to how a turbine will perform. In his paper, Wang (2008) defines design to achieve the best possible performance. He proves that the design of the blades can lead to higher effectiveness. Moreover, he concludes that the blade's geometric shape, the component connection, and the overall design influence the annual energy yield (Wang et al. 2008).

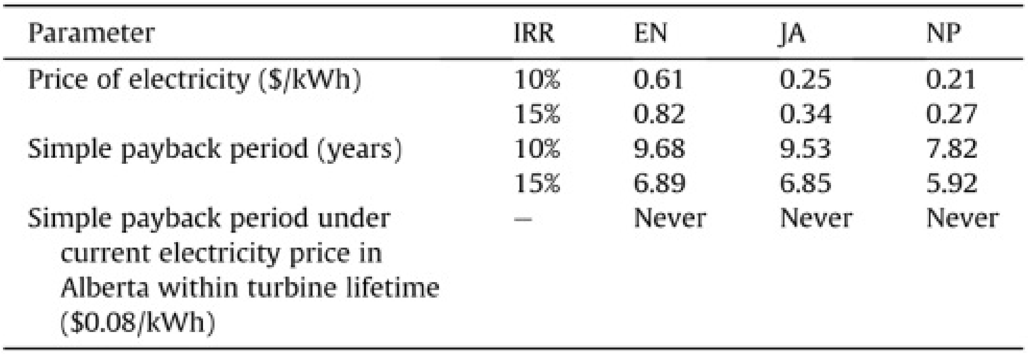
In addition, the tip speed ratio is affected by shape as well as solidity. Because giving the blade a direction to the tip achieves an evenly distributed pressure. At the tip, the incoming wind is faster; thus, the flow is slower at the center than the edge, which means a more robust flow near the tips, therefore, a larger torque (Wang et al. 2008). Furthermore, with increasing thickness, the tip speed ratio decreases, and the Maximum Power Coefficient increases. Moreover, increased solidity lowers the instant angle and gives a higher blade velocity (Rezaeiha et al. 2018); therefore, more wind harvesting.

To sum up, for small to medium-sized wind turbines, solidity is advised to remain low, as such turbines are required to work continuously and in environments that do not favor a medium or high tip speed. Moreover, more blades equal more power and rigid loads (Rezaeiha et al. 2018). Connection methods do not affect the performance a lot; the annual performance is affected more by meteorological state and urban morphology (Wang et al. 2008), therefore small wind turbine design should focus more on the blades and the solidity.

4.1.4 Investment cost of Small Wind Turbines

After reviewing the three graphs on page 46, the HALO brand is supplying a better investment return. An explanation for that is that HALO is offering their turbine at a lower price than the other two. Moreover, it can be noticed that there is a higher chance of recovering the cost of investment at places with higher wind speeds since all three turbines provide better results at higher wind speeds. Additionally, countries with lower electricity prices illustrate losses rather than gains.

Moreover, considering research from a financial point of view, Kabir (2012) concludes that implementing SWTs does not benefit the investor. The table below is part of Kabir’s findings and describes Canada's economic factors (Figure 26). The table illustrates that with the current power price in Alberta, Canada, (where the study is taking place), return on investment will never occur (Kabir et al. 2012).



Parameter	IRR	EN	JA	NP
Price of electricity ($/kWh)	10%	0.61	0.25	0.21
	15%	0.82	0.34	0.27
Simple payback period (years)	10%	9.68	9.53	7.82
	15%	6.89	6.85	5.92
Simple payback period under current electricity price in Alberta within turbine lifetime ($0.08/kWh)	–	Never	Never	Never

Figure 26 Table Illustrating Alberta's return on investment of small wind turbines (source: Kabir et al. 2012 p.140).

Furthermore, recent research regarding the financial profit of SWTs in London shows that the installation gave the building expenses a low profit compared to the total electricity expenses (Dymock 2013). Moreover, the SWT did not contribute to reducing CO_2 emissions from the building.

Furthermore, considering the potential for electricity generation in Vienna, results show that the investment is costly. Table 21 in page 52, shows that by installing twenty-one wind turbines per flat roof on the city's buildings, a budget of 3000 Million Euros would be required to cover approximately 50% of the city's electricity demand. As both numbers (number of turbines and budget) are somewhat unrealistic in sense of weight on the structure and funding; a more pragmatic solution would be installing less turbines per flat roof. Less turbines would count at half of the previous cost, however, then the electricity coverage would be very low.

In addition, a factor that raises the cost of SWTs is how and where they are produced (life cycle assessment). When importing a technology, it raises the cost, therefore makes the investment more expensive. Moreover, the CO_2 exerted for producing the turbine is another aspect to consider for the technology's viability. A study on SWT life cycle assessment shows that the most emission inducive processes are production, transportation, and installation. (Kabir et al. 2012)

Conclusively, with low electricity prices, implementing small wind turbines in urban space will not bring great results that would make the investment worth profiting. From the graphs listed on page 46 (Figure 19, Figure 20, Figure 21), it can be observed that the technology will not provide any profit for as long as electricity remains cheap.

4.2 The Future of Small Wind Turbines

Small wind turbines have been the topic of this thesis, and the future of their implementation is an important aspect of arguing that the technology is useful, especially with scientific research that can provide solutions to previous issues. State of the art projects demonstrate that small projects can be incorporated in the city and create a large scale wind farm if implemented broadly.

4.2.1 The Importance of Science in Future Implementation

Scientific research can provide valuable knowledge to planning building-integrated turbines or city planners aiming to incorporate small wind turbines in city plots. Stakeholders rely on Research and Development to improve the performance and cost of small wind turbines. An example of stakeholder involvement in research and development is NREL, the US's National Renewable Energy Laboratory. Through collaboration with manufacturers, they have achieved minimizing cost for users of SWTs (Cesar et al. n.d.).

In addition, for building incorporated turbines, research has aimed to improve the structural downsides of SWTs. For example, a simulation method called NSET helps recognize the exact spot where vibrations occur on a turbine (Rahman Elbakheit 2013). This tool can help engineers reduce one of the most significant issues of building integrated STWs; vibrations that cause building movement and occupant discomfort. Generally, the most used tool in applying wind turbines in an urban environment is the CFD simulations. With that, the user can create atmospheric situations that are close to reality and avoid implementation faults.

Moreover, research is not restrained to only numerical simulations such as CFD and occupant and user satisfaction. Aiming to a spherical representation of SWTs, Dymock (2013), in his study, provides a scope of urban wind turbine use by studying two cases (One of a roof-mounted turbine and the other of a building integrated turbine). The study's procedure is through surveys, numerical modeling, and assessment, so the author concludes with what will help enhance the case studies.

Research in existing projects can provide results that will help enhance the technology, even when it is already implemented and has failed. Research on both small- and large-scale projects depends on the background of the study. In the next paragraphs, research on large scale projects will be presented.

4.2.2 State of the Art and the Praxis

Projects that have implemented small wind turbines are a source of knowledge for the future of the technology. There are cases where incorporating SWTs has proven unsuccessful. For example, the Strata Tower in London was a promising investment for the city of London. However, implementation was poorly done, and the turbines did not perform as expected.

The Strata Tower consists of three turbines on the top of the building, more specifically at a 148 meters height (Table 6 p.32). The turbines are Horizontal Axis and are placed on an angled roof inside cylindrical openings. The developers' promising claim was that incorporating the turbines would count for 8% of the building’s energy consumption needs; however, these numbers were never achieved ("The rarely spinning turbines of the Strata Tower" 2011). Moreover, occupants of the upper-level apartments have reported disturbing vibrations and sound pollution (Londonist 2010). Studies on the lack of efficiency of the Strata Tower have been performed to improve the performance. According to Ramboll et.al

(2008), the tower's design was focused more on minimizing turbulent flow and steer wind flow; however, orientation failed to improve wind flow.

Kompatscher (2015) considers her base case to be Strata Tower as it stands today and suggests a reform of the initial shape of the turbine's cross-section by incorporating two more shapes in the design. For the first alteration, a nozzle and the second a diffuser are added (Figure 27). Afterward, different positions concerning the height of the building are introduced. In addition, considering that stagnation on a building happens at 70% of the building height, the turbines are lowered to that height. Moreover, to prove that height influences performance, the turbines are placed in the lowest height possible (Figure 28), at 10% of the total building height, where results show poor performance.

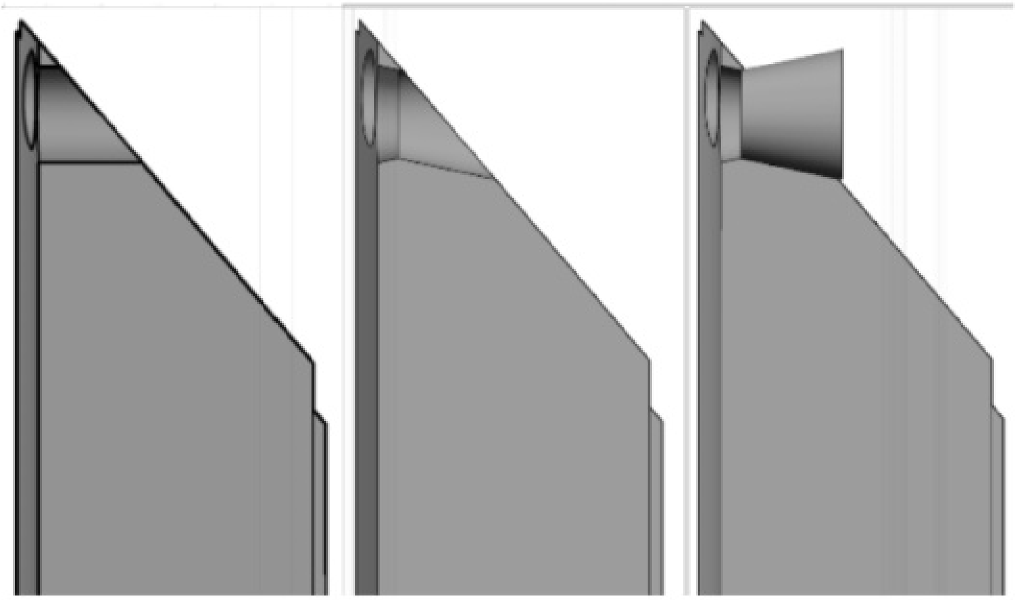


Figure 27 Strata Tower turbine design suggestions (source: Kompatscher 2015)

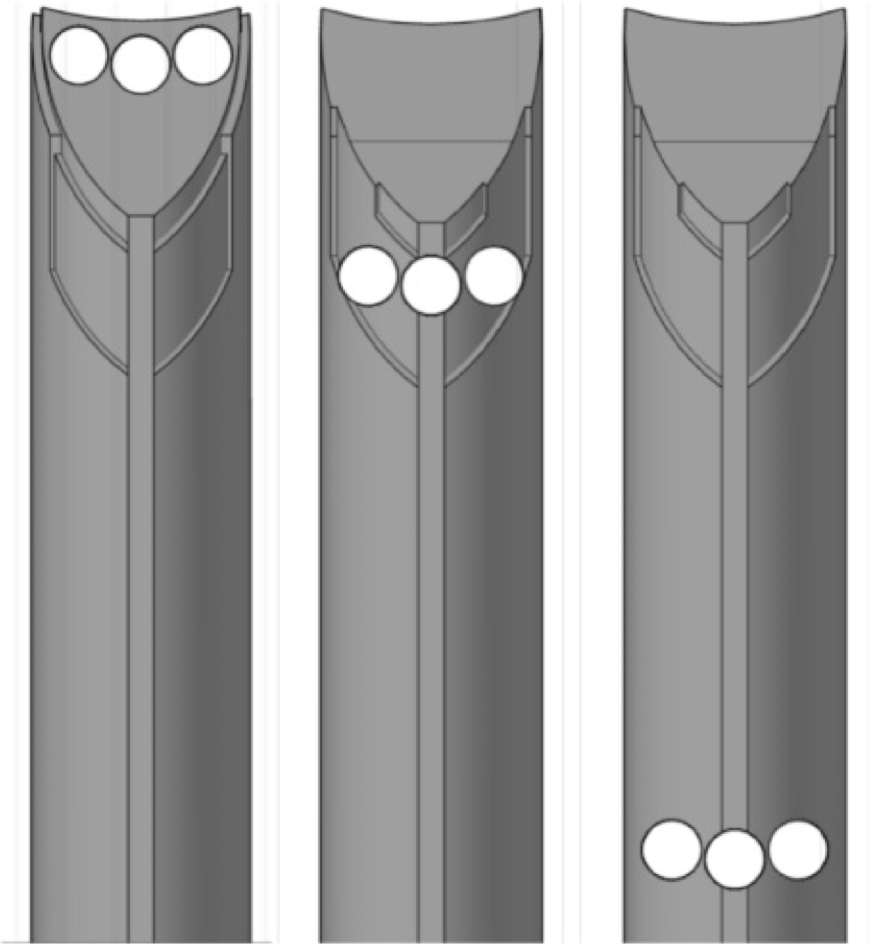


Figure 28 Strata Tower turbine position suggestion (source: Kompatscher 2015)

However, only one wind direction is not representative of real conditions. Therefore, various wind directions are studied to showcase the different efficiencies according to the position. To confirm that the shape that engineers gave to the roof to help the performance, the flow separation is studied. It is noticeable that the sloped roof is of help to wind amplification, especially when winds come from the north at 180 degrees direction. (Kompatscher 2015)

Like Kompatscher, Dymock (2013) studied the strata Tower problematic and his proposal to improve the turbine performance is something quite impossible, as he suggests rotating the whole building. Despite Strata's height being at optimal altitude so that interferences do not occur, and the venturi turbines can benefit from occurring windspeeds, the building's orientation disrupts the wind speed causing a mean wind speed of 0,75 m/s. The author proposes a 25-degree clockwise shift of the building in order to have more southern winds. The shift would result in +10,5MWh of yield, an increase that would help reach the 8% of covering electrical needs. (Dymock and Dance 2013)

Dymock (2013) did not narrow his research only to a large scale project, but he also studied a stand-alone turbine and the effects of the surroundings. Therefore, he performed an atmospheric study for SWTs in the London South Bank University plot where the problem of the turbine position, in this case, is that it has a building that is reducing the turbulent wake, thus reducing the mean wind speed. In a hypothetical scenario where the turbine is placed 10 meters higher, a 40% increase in wind speed is noticed. The author also proposes to add isolation between the base of the turbine and the surface where it lays. The proposed solution will separate the base to the surface and provide lower vibrations to the building. (Dymock and Dance 2013)

Another example of building augmented turbines is the Bahrain World Trade Center, the first building to implement the technology. The structure consists of two towers connected through bridges, and these bridges support the turbines (Table 6). In order to have the same wind velocity on all three turbines, the towers (Figure 14) have a rounded shape ("Bahrain World Trade Centre" n.d.). Despite of the turbines covering between 11% and 15% of the building's energy consumption, professor Blocken (2020) claims that a 180-degree turn of the turbines would generate 31% more power ("Windmills on the sky building generate 15% less energy" 2020).

The project of the Bahrain World Trade Center combined the work of architects' engineers and wind turbine specialists. The focus of engineers was to raise the turbines' efficiency so that they can cover the goal of covering 11%-15% of the energy consumption. The building is an example that performance like that is achievable when proper planning is involved. Proper planning is performing CFD simulations, which help give a first impression of how the project will carry out. As Saeed (2017) indicates, the completed work has a few faults in structure and technology that could have been avoided with rigorous wind tunnel simulations. However, Moghadam (2018)- that performed wind tunnel simulations on the same building- points out that the tests should be carried out with the turbines included. Otherwise, the results show 15% more potential for wind energy production. Moghadam's research verifies that simulations need to be carried out meticulously to present a realistic reflection of the project.

The projects presented in this Master Thesis are a few of the most well-known examples of SWTs in cities. The uniqueness of these projects and what makes them world-famous is that they involve building-integrated turbines. Moreover, the advantage of that technology lies on the fact that turbines can be harmoniously incorporated in the urban canopy, since there is a concern of whether SWTs are suitable to be implemented in cities.

Ultimately, from the studies on the state of the art, the actual implemented turbines will function adequately with proper simulations. There are a plethora of failed and successful examples of SWT implementation. To evolve the technology, one should consider both examples, as these will show the path to improvement.

5 CONCLUSION

Implementing wind turbines in cities is somewhat unpopular, since there is a problematic to the technology; it depends on weather conditions and fluctuations of the electricity market, and it has statical and visual impacts on structures. Therefore, the investment is risky enough for individuals, and the SWTs are not the first choice when deciding to upgrade the performance of either a building or a community. However, some advantages can prove otherwise.

For the completion of this literature review, the tools that were used were online databases. Through these tools and the selection criteria, a handful of research papers is presented. The papers are classified according to the thematic category and presented on tables. From this classification, the reader can quickly scan through the information provided. In addition, a rough estimation for SWTs on flat roofs in Vienna illustrates the capability of SWTs in covering the electricity consumption of a city.

Scientific research focuses on enhancing the performance and the annual energy yield that a turbine can offer. That happens through studying the design, as well as the location of small wind turbines. The most common methodology to investigate a turbine’s performance is through CFD simulations. With CFD simulations, the turbine's airflow can be determined and, therefore, the energy output. The frequently used tool is ANSYS fluent, a tool that is designed to provide results for fluid physics problems. Through numerical simulations, the research papers that were reviewed provide visual representations of performance under different conditions. Out of the 28 reviewed papers, 13 of them use numerical simulations to study and analyze performance. Moreover, the research papers' results showcase a tendency towards more efficient design in horizontal axis wind turbines.

The studies consider the place of the turbine as a prerequisite for efficient function and the building's shape. Despite shape influencing performance (because it can create turbulence), a more critical factor is the turbine's placement height. Therefore, according to the studies presented in this thesis, the most efficient position of placing a wind turbine would be the rooftop of a building where wind conditions are smoother and more favorable to performance.

Regarding technological advancements, manufacturers aim to provide high performance in low wind speeds and design that can be harmonically incorporated in cities. The need for more adaptability to the environment design has brought companies to think out of the box and produce wind turbines that do not follow traditional shapes. What boosts the drive for innovation is the limitations for visual disturbance in the city. Moreover, size is of interest when installing a small wind turbine, as it is visually significant, but it is also relevant for energy harvesting. However, looks and efficiency contradict one another; on the one hand, a small wind turbine should be small enough not to visually impact a city's characteristics. On the other hand, the bigger the size, the better the wind harvesting and electricity production.

Furthermore, regarding wind energy generation policies in cities, the rough estimation for the city of Vienna showed that the required budget to cover a high percentage of the electricity demand is very high, and it is questionable whether municipalities would fund such a project. The use of the technology has been influenced by the electricity prices and use of other renewable alternatives; however, a plausible solution to SWTs would be collaborative funding between the state and private sectors to boost the use of that form of renewable energy.

Future research themes instrumental to the further development of the topic would be to focus on making turbines lighter without losing stability and their energy generation capacity. Because, not only would they not impose much weight on the structure and look unappealing, but their vibrations could also be reduced not to disturb the occupants. Also, creating open-source simulation programs would make research more accessible and, therefore, easier for engineers to consider using them. Because, as observed in the studies, simulation tools are crucial to implementing small wind turbines in cities. However, these tools are costly, and most engineers do not acquire them. Therefore, future research should focus on more open-source software tools to help engineers analyze and install small wind turbines on buildings and cities.

Ultimately, what can be derived from the collection of information in this thesis is that computational fluid dynamics play a crucial role in predicting the performance and optimize the location of small wind turbines. Moreover, producing a statistical analysis of the turnover showed that return on investment for small wind turbines depends on electricity prices, and for as long as these are kept low, there is no substantial turnout. Therefore, potential investors will be hesitant to install small wind turbines. However, it is essential to understand that a financial benefit should not be the bigger drive for choosing renewable energy sources on buildings but the benefit that renewables bring to the environment.

6 INDEX

6.1 List of Figures

6.2 List of Tables

6.3 List of Equations

7 LITERATURE

All sources (books, journals, internet documents...), which were used in the work, are listed in the following:

Abohela, I., Hamza, N. and Dudek, S. (2013) ‘Effect of roof shape, wind direction, building height and urban configuration on the energy yield and positioning of roof mounted wind turbines’, *Renewable Energy*, 50, pp. 1106–1118. doi: 10.1016/j.renene.2012.08.068.

AEOLOS (2020). Available at: https://www.windturbinestar.com/ (Accessed: 4 October 2020).

Aerocraft (2016). Available at: http://www.aerocraft.de/aerocraft.html (Accessed: 4 October 2020).

Akwa, J. V., Vielmo, H. A. and Petry, A. P. (2012a) ‘A review on the performance of Savonius wind turbines’, *Renewable and Sustainable Energy Reviews*. Pergamon, pp. 3054–3064. doi: 10.1016/j.rser.2012.02.056.

Akwa, J. V., Vielmo, H. A. and Petry, A. P. (2012b) ‘A review on the performance of Savonius wind turbines’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 16(5), pp. 3054–3064. doi: 10.1016/j.rser.2012.02.056.

Arteaga-López, E., Ángeles-Camacho, C. and Bañuelos-Ruedas, F. (2019) ‘Advanced methodology for feasibility studies on building-mounted wind turbines installation in urban environment: Applying CFD analysis’, *Energy*. Elsevier Ltd, 167, pp. 181–188. doi: 10.1016/j.energy.2018.10.191.

Bahrain World Trade Centre (no date). Available at: https://www.designbuild-network.com/projects/bahrain-world-trade-centre/ (Accessed: 1 August 2020).

Bergey WindPower (no date). Available at: http://www.bergey.com/ (Accessed: 4 October 2020).

Bichet, A. Wild, M., Folini, D., Schr, C. (2012) ‘Causes for decadal variations of wind speed over land: Sensitivity studies with a global climate model’, *Geophysical Research Letters*. Blackwell Publishing Ltd, 39(11). doi: 10.1029/2012GL051685.

Blanco, M. I. (2009) ‘The economics of wind energy’, *Renewable and Sustainable Energy Reviews*, pp. 1372–1382. doi: 10.1016/j.rser.2008.09.004.

Bobrova, D. (2015) ‘Building-integrated wind turbines in the aspect of architectural shaping’, *Procedia Engineering*. Elsevier B.V., 117(1), pp. 404–410. doi: 10.1016/j.proeng.2015.08.185.

Bornay (2017). Available at: https://www.bornay.com/en (Accessed: 4 October 2020).

Botha, J. D. M., Rasam, A., Catháin, D., Rice, H., Shahrokhi, A. (2016) 'Some noise predictions for small wind turbines', *Proceedings of ISMA 2016 - International Conference on Noise and Vibration Engineering and USD2016 - International Conference on Uncertainty in Structural Dynamics*, pp. 4019–4032.

Braun Windturbinen (2013). Available at: https://www.braun-windturbinen.com/start/ (Accessed: 4 October 2020).

Brit Wind (no date). Available at: http://www.britwind.co.uk/ (Accessed: 4 October 2020).

Building-integrated wind turbines (2016) *Climate Technology Centre and Network*. Available at: https://www.ctc-n.org/technologies/building-integrated-wind-turbines (Accessed: 1 January 2021).

Can, H., (2020) 'Small Wind Guidebook', pp. 1–22.

Casini, M. (2015) 'Small Vertical Axis Wind Turbines for Energy Efficiency of Buildings', *Journal of Clean Energy Technologies*. EJournal Publishing, 4(1), pp. 56–65. doi: 10.7763/jocet.2016.v4.254.

Cesar, C., Chagas, M., Pereira, M., Rosa, L., Fidelis Da Silva, N., Aurélio, M., Freitas, V., David H., (2020) 'sustainability Review From Megawatts to Kilowatts: A Review of Small Wind Turbine Applications, Lessons From The US to Brazil'. doi: 10.3390/su12072760.

Charabi, Y. and Abdul-Wahab, S. (2020) 'Wind turbine performance analysis for energy cost minimization', 7, p. 5. doi: 10.1186/s40807-020-00062-7.

Ciobanu, D., Gheorghe, M., Saulescu, R., Midoi, B., Jaliu, C., (2019) 'The effect of urban buildings on the implementation of small wind turbines', *IOP Conference Series: Materials Science and Engineering*, 514, p. 012028. doi: 10.1088/1757-899x/514/1/012028.

Cities are at the frontline of the energy transition - News - IEA (no date). Available at: https://www.iea.org/news/cities-are-at-the-frontline-of-the-energy-transition (Accessed: 17 December 2019).

City of Vienna (2018) *Energy ! ahead - Energy Report of the City of Vienna*. Vienna.

Cooney, C., Byrne, R., Lyons, W., O'Rourke, F. (2017) 'Performance characterisation of a commercial-scale wind turbine operating in an urban environment, using real data’, *Energy for Sustainable Development*. Elsevier B.V., 36, pp. 44–54. doi: 10.1016/j.esd.2016.11.001.

Dahirul Islam, K., Taweekun, J. and Theppaya, T. (2020) ‘Investigation of Small Wind Turbine Noise as per IEC 61400-11 and AWEA 9.1 Standard’, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences Journal homepage*, 74, pp. 183–195. doi: 10.37934/arfmts.74.2.183195.

Dang, M., Achammer, C. M., Gartner, G., Sampaio, M., (2019) *Doctoral Thesis Investigating the 5th facades of cities : A parametric computational model of urban agriculture potentials Ein parametrisches Modell welches die Potenziale der städtischen Landwirtschaft aufzeigt “ Designing a dream city is easy ; rebuildi*.

Dixon, S. L., Hall, C.A., (2014) ‘Chapter 10 – Wind Turbines’, in *Fluid Mechanics and Thermodynamics of Turbomachinery*. Butterworth-Heinemann, pp. 419–485. doi: 10.1016/B978-0-12-415954-9.00010-3.

Dymock, B. and Dance, S. (2013) ‘Building integrated wind turbines - A pilot study’, *Proceedings of Meetings on Acoustics*, 19. doi: 10.1121/1.4799234.

Dymock, B. R. (2013) *Urban Wind Turbines : A Feasibility Study*. London South Bank University.

ElCheikh, A., Elkhoury, M., Kiwata, T., Kono, T. (2018) ‘Performance analysis of a small-scale Orthopter-type Vertical Axis Wind Turbine’, *Journal of Wind Engineering and Industrial Aerodynamics*. Elsevier B.V., 180, pp. 19–33. doi: 10.1016/j.jweia.2018.07.008.

Emejeamara, F. C. and Tomlin, A. S. (2020) ‘A method for estimating the potential power available to building mounted wind turbines within turbulent urban air flows’, *Renewable Energy*. Elsevier Ltd, 153, pp. 787–800. doi: 10.1016/j.renene.2020.01.123.

ENERCON (2016). Available at: https://www.enercon.de/en/products/ (Accessed: 4 October 2020).

Fleming, P. D. and Probert, S. D. (1984) ‘The evolution of wind-turbines: An historical review’, *Applied Energy*, 18(3), pp. 163–177. doi: 10.1016/0306-2619(84)90007-2.

Fortis Wind Energy (no date). Available at: https://www.fortiswindenergy.com/ (Accessed: 4 October 2020).

Ghaith, A. F., Epplin, F. M. and Frazier, R. S. (2017) ‘Economics of household wind turbine grid-tied systems for five wind resource levels and alternative grid pricing rates’, *Renewable Energy*. Elsevier Ltd, 109, pp. 155–167. doi:

10.1016/j.renene.2017.03.033.

Global Wind Power Statistics – Wind Energy International Platform (no date). Available at: https://library.wwindea.org/global-statistics/ (Accessed: 9 November 2020).

Gsänger, S. and Pitteloud, J.-D. (2015) ‘2015 Small Wind World Report Summary.’, p. 15. Available at: www.wwindea.org (Accessed: 19 December 2019).

Guarnieri, M. (2017) ‘“Blowin’’ in the Wind" [Historical]”’, *IEEE Industrial Electronics Magazine*, 11(1). doi: 10.1109/MIE.2017.2652798.

halo ENERGY (no date). Available at: https://www.halo.energy/ (Accessed: 4 October 2020).

Hashem, I., Mohamed, M. H. and Hafiz, A. A. (2017) ‘Aero-acoustics noise assessment for Wind-Lens turbine’, *Energy*. Elsevier Ltd, 118, pp. 345–368. doi: 10.1016/j.energy.2016.12.049.

Heo, Y. G., Choi, N. J., Choi, K. H., Ji, H. S., Kim, K. C. (2016) ‘CFD study on aerodynamic power output of a 110 kW building augmented wind turbine’, *Energy and Buildings*. Elsevier Ltd, 129, pp. 162–173. doi: 10.1016/j.enbuild.2016.08.004.

Hewitt, C. (2019) *Wind Generation in Urban Settings*, *Renewable Energy World*. Available at: https://www.renewableenergyworld.com/wind-power/wind-generation-in-urban-settings/#gref (Accessed: 1 September 2020).

Hodgson, E. V. F. (2004) *Contemporary Problems in Appropriate Technology Residential Wind Turbines and Noise Emissions*.

Ibrahim, A. (2019) ‘Highway Vertical Axis Wind Turbine with Vortex Generators’, (February).

IEA (2019) *2019 Global Status Report for Buildings and Construction*. Available at: www.iea.org (Accessed: 13 January 2020).

Inield, P. (2012) *Wind turbine tower vibration modelling and monitoring by the nonlinear state estimation technique (NSET). Energies.*

Ishugah, T. F., Li, Y., Wang, R. Z., Kiplagat, J. K. (2014) ‘Advances in wind energy resource exploitation in urban environment: A review’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 613–626. doi: 10.1016/j.rser.2014.05.053.

Johansson, L. (2000) *Summary of IEA Topical Expert meeting on Noise Immission*.

Kabir, M. R., Rooke, B., Dassanayake, G. D. M., Fleck, B. A. (2012) ‘Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation', *Renewable Energy*. Pergamon, 37(1), pp. 133–141. doi: 10.1016/j.renene.2011.06.003.

Kaufmann, H. and Tran, H. V. (2015) *Windzonierungskarte für Kleinwindkraftanlagen für Wien*. Available at: www.zamg.at (Accessed: 8 January 2021).

KC, A., Whale, J. and Urmee, T. (2019) 'Urban wind conditions and small wind turbines in the built environment: A review', *Renewable Energy*, 131(August), pp. 268–283. doi: 10.1016/j.renene.2018.07.050.

Kessler SPINWIND (2020). Available at: https://en.wind-turbine-models.com/turbines/1043-kessler-spinwind (Accessed: 4 October 2020).

Kliux (no date). Available at: http://www.kliux.com/en/.

Kompatscher, K. (2015) *Numerical study of wind energy harvesting by the Strata Tower*.

Main, K. T. H. (2013) 'Feasibility Study of Small Scale Standalone Wind Turbine for Urban Area'.

Li, Q. S., Shu, Z. R. and Chen, F. B. (2016) 'Performance assessment of tall building-integrated wind turbines for power generation', *Applied Energy*. Elsevier Ltd, 165, pp. 777–788. doi: 10.1016/j.apenergy.2015.12.114.

Manganhar, A. L., Rajpar, A. H., Luhur, M. R., Samo, S. R., Manganhar, M. (2019) 'Performance analysis of a savonius vertical axis wind turbine integrated with wind accelerating and guiding rotor house', *Renewable Energy*. Elsevier Ltd, 136, pp. 512–520. doi: 10.1016/j.renene.2018.12.124.

Marlec (2020). Available at: https://www.marlec.co.uk/ (Accessed: 4 October 2020).

Ministry of Foreign Affairs, R. of C. (2013) 'ROC launches small wind turbine certification'. Ministry of Foreign Affairs, Republic of China (Taiwan). Available at: https://taiwantoday.tw/news.php?unit=6&post=11702 (Accessed: 5 January 2021).

new world wind (2020).

Offene Daten Österreich | data.gv.at (no date). Available at: https://www.data.gv.at/ (Accessed: 15 January 2021).

Van Overeem, S., Alen, L., Brouwer, Y., Van Dam, A. D., Van Dekken, G. M., Garrett, G. H., Geboers, S., Poland, J. A. W., Aldridge, H. W. S., Dighe, V. V., Chrysochoidis-Antsos, N. (2017) 'Wind assessment for micro wind turbines in an urban environment', *International Journal of Energy Production and Management*. WITPress, 2(4), pp. 327–338. doi: 10.2495/EQ-V2-N4-327-338.

Pitteloud, J.-D. and Gsänger, S. (2017) *2017 Small Wind World Report Summary*. Available at: www.wwindea.org (Accessed: 19 December 2019).

Quiet Revolution (2020). Available at: https://www.quietrevolution.com/ (Accessed: 4 October 2020).

Rahman Elbakheit, A. (2013) 'Wind-Induced Vibrations to Tall Buildings and Wind Turbines', *Web of science*, p. 29. doi: http://dx.doi.org/10.5772/46845.

renewable devices (no date). Available at: http://www.renewabledevices.com/ (Accessed: 4 October 2020).

Rezaeiha, A., Montazeri, H. and Blocken, B. (2018) 'Towards optimal aerodynamic design of vertical axis wind turbines: Impact of solidity and number of blades', *Energy*. Elsevier Ltd, 165, pp. 1129–1148. doi: 10.1016/j.energy.2018.09.192.

RWE npower renewables (2007) 'Wind Turbine Power Calculations', *The Royal Academy of Engineering*. Available at: https://www.raeng.org.uk/publications/other/23-wind-turbine (Accessed: 9 December 2019).

RyseEnergy (2020). Available at: https://www.gaia-wind.com/ (Accessed: 4 October 2020).

Saeed, S. A. (2017) 'The Feasibility of Utilizing Wind Energy in Commercial Buildings With Special Reference to the Kingdom of Bahrain', in *World Renewable Energy Congress-17*. doi: 10.1051/e3sconf/20172309001.

Saleh, A. and Feeny, B. F. (2019) 'Modal analysis of a vertical-axis darrieus wind turbine blade with a troposkein shape', in *Conference Proceedings of the Society for Experimental Mechanics Series*. Springer New York LLC, pp. 325–327. doi: 10.1007/978-3-319-74700-2_36.

Santamouris, M. (no date) *Energy Consumption in the European Built Environment The Role of Cooling*.

Sarkar, A. (2012) 'Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy', *International Journal of Scientific and Research Publications*, 2(2), p. 1. Available at: www.ijsrp.org (Accessed: 9 January 2020).

Sarkar, A. and Kumar Behera, D. (2012) 'Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy', *International Journal of Scientific and Research Publications*, 2(2).

Schwartz, A. (2010) *Strata Tower: The First Building With Wind Turbines Incorporated Into Its Design*, *Fastcompany.com*. Available at:

https://www.fastcompany.com/1583813/strata-tower-first-building-wind-turbines-incorporated-its-design.

Shahin, H. (2020) *Bahrain World Trade Center | Killa Design*.

Shepherd, D. G. (2010) ‘Historical Development of the Windmill’, *Wind Turbine Technology: Fundamental Concepts in Wind Turbine Engineering, Second Edition*, pp. 1–46. doi: 10.1115/1.802601.ch1.

Simiu, E. and Scanlan, R. (1996) *Wind Effects on Structures*. Third. John Wiley & Sons.

SINNPOWER (2019). Available at: https://www.sinnpower.com/post/sinn-power-supplies-more-small-wind-turbine-developers-with-state-of-art-wind-technology (Accessed: 6 October 2020).

Smith, R. F. and Killa, S. (2007) ‘Subject: Building Case Study Wind Engineering Paper Title: Bahrain World Trade Center (BWTC): The First Large-Scale Integration of Wind Turbines in a Building BAHRAIN WORLD TRADE CENTER (BWTC): THE FIRST LARGE-SCALE INTEGRATION OF WIND TURBINES IN A BUILDING’. doi: 10.1002/tal.416.

Statistik Austria (2018). Available at: http://statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energieeinsatz_der_haushalte/index.html.

Sugahara, M. (no date) *Energy and Resilient Cities.pdf*. OECD.

Techcarbon (2017) *Techcarbon*. Available at: http://www.wind-of-change.org/index.php/home_helix.html.

Teh, A. (2016) *STRATA SE1 – ELEPHANT & CASTLE TOWER*. Available at: http://epxeteh.blogspot.com/2016/12/5-nov-2016-strata-tower-se1.html (Accessed: 27 December 2020).

The rarely spinning turbines of the Strata Tower, south London (2011). Available at: http://www.urban75.org/blog/the-rarely-spinning-turbines-of-the-strata-tower-south-london/ (Accessed: 3 August 2020).

The World’s Cities in 2016 Data Booklet (no date). Available at: www.unpopulation.org. (Accessed: 17 December 2019).

Toja-Silva, F., Kono, T., Peralta, C., Lopez-Garcia, O., Chen, J. (2018) ‘A review of computational fluid dynamics (CFD) simulations of the wind flow around buildings for urban wind energy exploitation’, *Journal of Wind Engineering and Industrial Aerodynamics*. Elsevier B.V., 180, pp. 66–87. doi: 10.1016/j.jweia.2018.07.010.

Unger, R. W. (2013) ‘Energy Transitions in History’.

V-Air (2018). Available at: http://www.visionairwind.com/ (Accessed: 6 October 2020).

Vertical Wind (no date). Available at: http://www.verticalwindturbineinfo.com/vawt-manufacturers/sauer-energy/ (Accessed: 6 October 2020).

Wang, F., Bai, L., Fletcher, J., Whiteford, J., Cullen, D. (2008) ‘Development of small domestic wind turbine with scoop and prediction of its annual power output’, *Renewable Energy*, 33(7), pp. 1637–1651. doi: 10.1016/j.renene.2007.08.008.

Wien Umweltgut (no date). Available at: https://www.wien.gv.at/umweltgut/public/ (Accessed: 15 January 2021).

Wang, Q., Wang, J., Hou, Y., Yuan, R., Luo, K., Fan, J. (2018) ‘Micrositing of roof mounting wind turbine in urban environment: CFD simulations and lidar measurements’, *Renewable Energy*. Elsevier Ltd, 115, pp. 1118–1133. doi: 10.1016/j.renene.2017.09.045.

Wiener Solar-Potenzial (2020) *Stadt Wien*.

Wind turbines on city tower block (2005) *BBC News*. Available at: http://news.bbc.co.uk/2/hi/uk_news/england/manchester/4648371.stm (Accessed: 5 January 2021).

Windmills on the sky building generate 15% less energy (2020). Available at: https://www.betterworldsolutions.eu/windmills-on-the-sky-building-generate-15-less-energy/ (Accessed: 5 August 2020).

WMO (no date) *W0 R L D MET E 0 R 0 LOG I C A L o R G A N I Z A T ION MARINE METEOROLOGY AND RELATED OCEANOGRAPHIC ACTIVITIES REPORT*.

Yang, A. S., Su, Y. M., Wen, C. Y., Juan, Y. H., Wang, W. S., Cheng, C. H. (2016) ‘Estimation of wind power generation in dense urban area’, *Applied Energy*. Elsevier Ltd, 171, pp. 213–230. doi: 10.1016/j.apenergy.2016.03.007.

Yip, B. (2010) ‘The Pearl River Tower’, *Reuters Pictures*. Available at: https://pictures.reuters.com/archive/CHINA--GM1E68O10OT01.html#/SearchResult&ITEMID=GM1E68O10OT01&POPUPPN=1&POPUPIID=2C04080CXN7HW (Accessed: 22 November 2020).

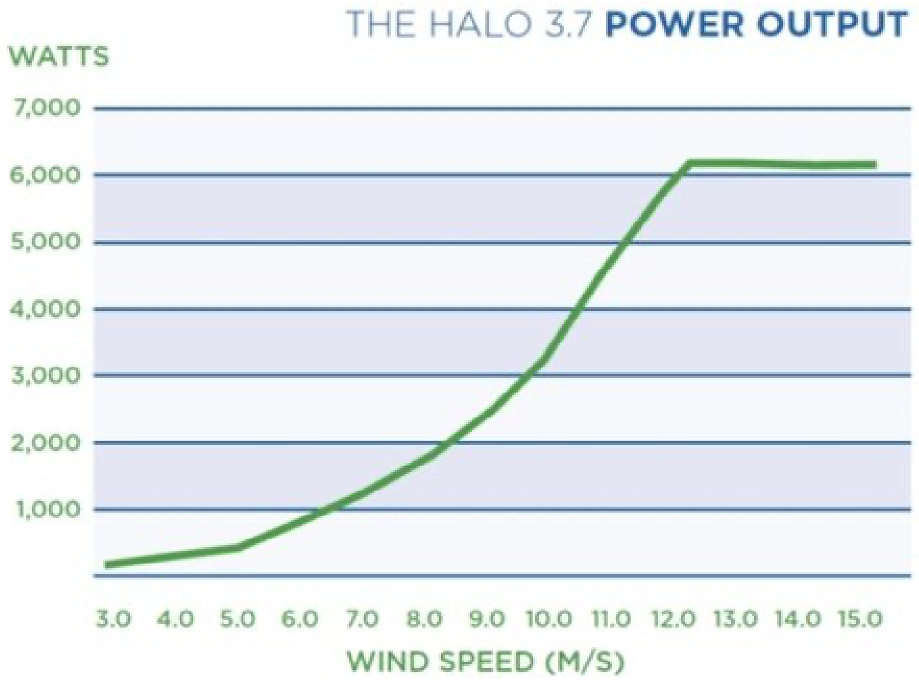
Zabarjad Shiraz, M., Dilimulati, A. and Paraschivoiu, M. (2020) ‘Wind power potential assessment of roof mounted wind turbines in cities’, *Sustainable Cities and Society*. Elsevier B.V., 53, p. 101905. doi: 10.1016/j.scs.2019.101905.

Zanforlin, S. and Letizia, S. (2015) ‘Improving the performance of wind turbines in urban environment by integrating the action of a diffuser with the aerodynamics of the rooftops’, in Energy Procedia. Elsevier Ltd, pp. 774–781. doi: 10.1016/j.egypro.2015.11.810.

8 APPENDIX

A. Figures

Figure 1 Power output and Annual energy production graphs of Halo 3.7 turbine (turbine used for Vienna estimation) (source: Halo ENERGY)



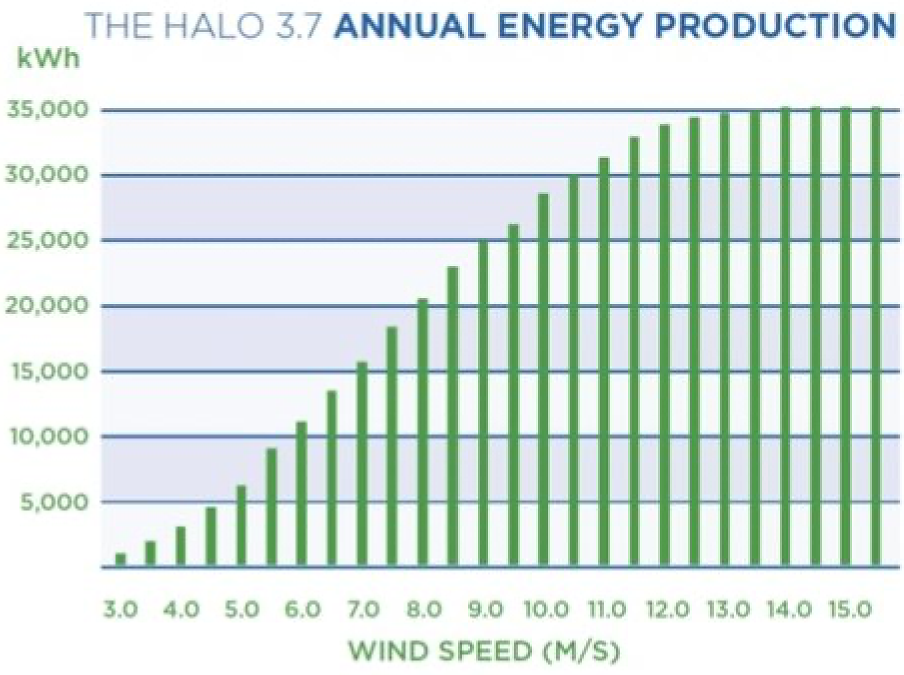
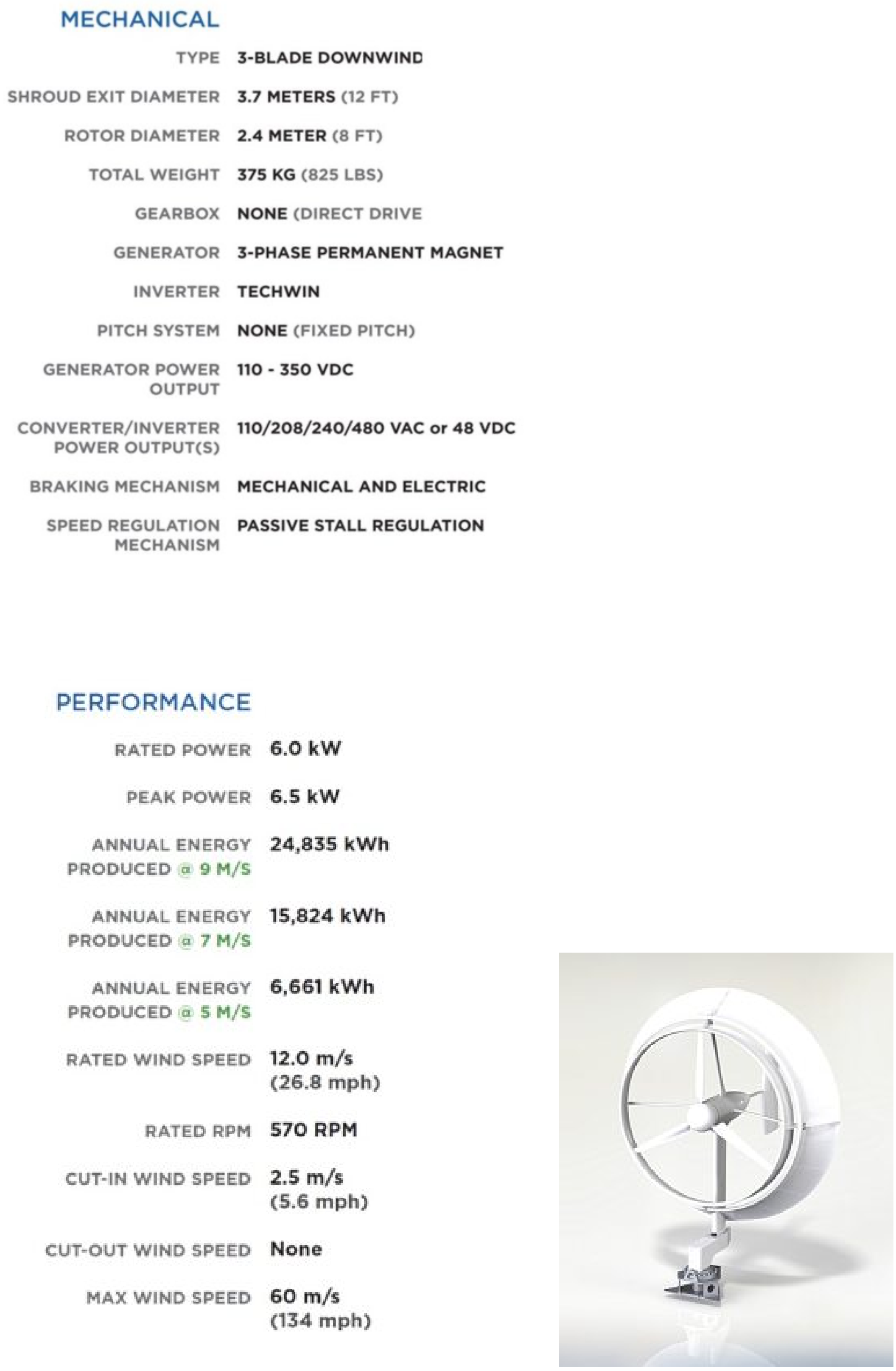


Figure 2 Mechanical and performance data of Halo 3.7 turbine (source: Halo ENERGY)



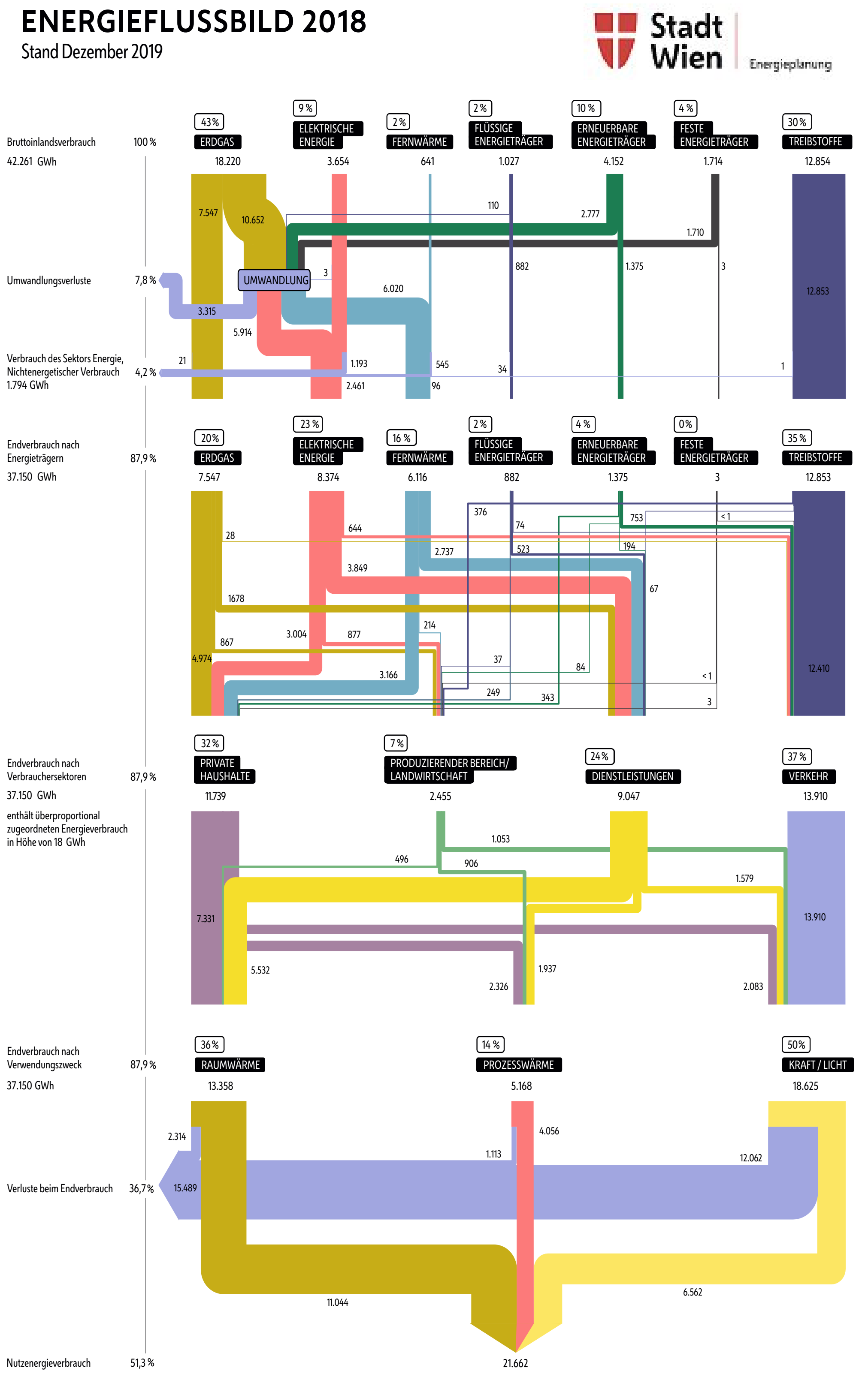
MECHANICAL

TYPE	3-BLADE DOWNWIND
SHROUD EXIT DIAMETER	3.7 METERS (12 FT)
ROTOR DIAMETER	2.4 METER (8 FT)
TOTAL WEIGHT	375 KG (825 LBS)
GEARBOX	NONE (DIRECT DRIVE
GENERATOR	3-PHASE PERMANENT MAGNET
INVERTER	TECHWIN
PITCH SYSTEM	NONE (FIXED PITCH)
GENERATOR POWER OUTPUT	110 - 350 VDC
CONVERTER/INVERTER POWER OUTPUT(S)	110/208/240/480 VAC or 48 VDC
BRAKING MECHANISM	MECHANICAL AND ELECTRIC
SPEED REGULATION MECHANISM	PASSIVE STALL REGULATION

PERFORMANCE

RATED POWER	6.0 kW
PEAK POWER	6.5 kW
ANNUAL ENERGY PRODUCED @ 9 M/S	24,835 kWh
ANNUAL ENERGY PRODUCED @ 7 M/S	15,824 kWh
ANNUAL ENERGY PRODUCED @ 5 M/S	6,661 kWh
RATED WIND SPEED	12.0 m/s (26.8 mph)
RATED RPM	570 RPM
CUT-IN WIND SPEED	2.5 m/s (5.6 mph)
CUT-OUT WIND SPEED	None
MAX WIND SPEED	60 m/s (134 mph)

Figure 3 Vienna Energy Flows (source: City of Vienna 2018)



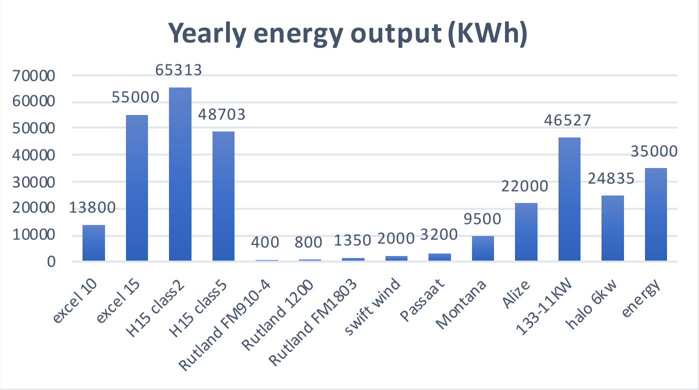
Energie-Einheit: 1 Gigawattstunde (GWh)= 10^6 kWh = 3,6 TJ = 3,6 * 10^{12} Joule

Quelle: Datenquelle Statistik-Austria Energiebilanzen 2018 / © MA20
Hinweis: Die Werte sind gerundet.

B. Tables

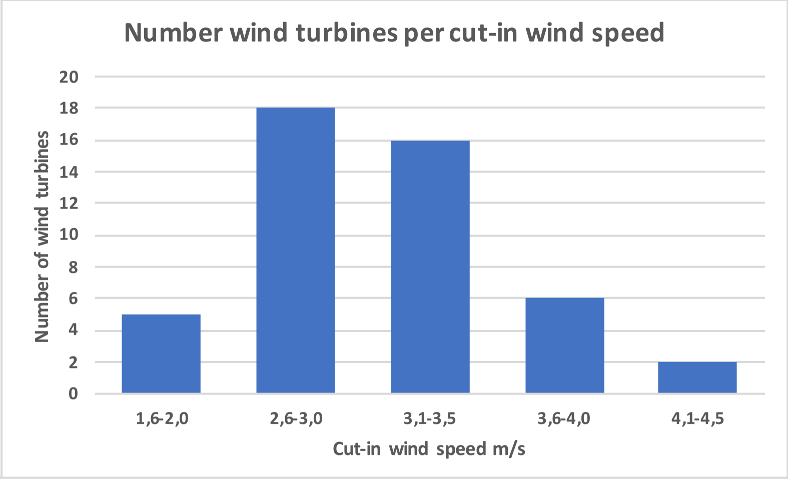
Calculation Table 1 Yearly energy output

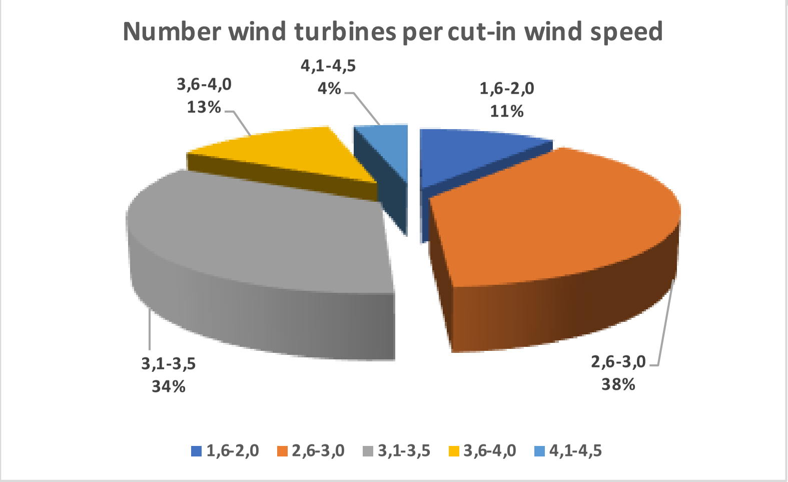
model	Yearly energy output (KWh)	at windspeed (m/s)
excel 10	13800	5
excel 15	55000	5
H15 class2	65313	8
H15 class5	48703	6
Rutland FM910-4	400	7
Rutland 1200	800	7
Rutland FM1803	1350	15
swift wind	2000	12
Passaat	3200	6
Montana	9500	6
Alize	22000	6
133-11KW	46527	7
halo 6kw	24835	9
energy	35000	15



Calculation Table 2 Cut-in windspeed and number of turbines

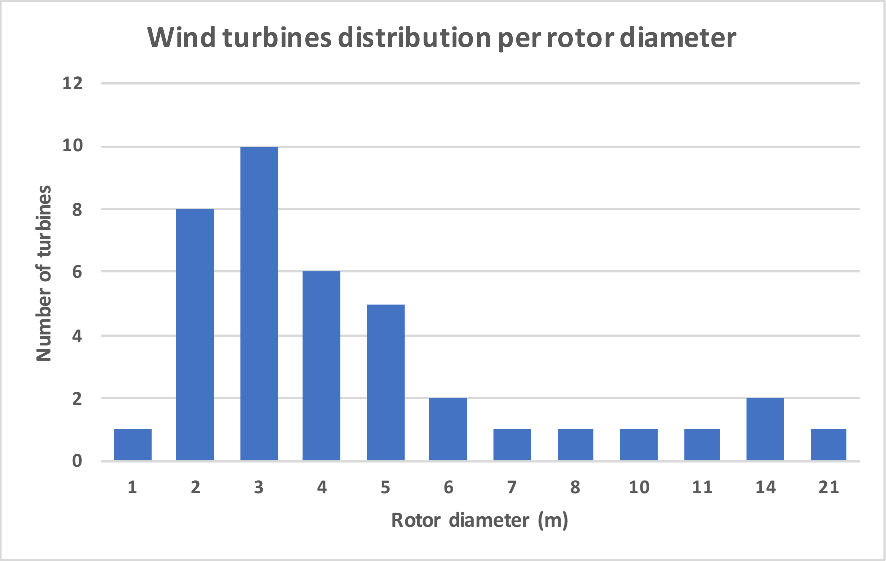
max	#REF!	min	#REF!
Cut-in			
Wind spee	number		
1	0		
1,5	0		
2	5		
2,5	5		
3	23		
3,5	39		
4	45		
4,5	47		
	23		
1,6-2,0	5		
2,6-3,0	18		
3,1-3,5	16		
3,6-4,0	6		
4,1-4,5	2		





Calculation Table 3 number of turbines and rotor diameter

Rotor diameter		
max		min
Diameter	Number	
1	1	1
2	9	8
3	19	10
4	25	6
5	30	5
6	32	2
7	33	1
8	34	1
10	35	1
11	36	1
14	38	2
21	39	1



Calculation Table 4 electricity prices per country (source: Eurostat 2019)

GEO/TIME	include taxes	exclude VAT	Without taxes	Other taxes	VAT
Ukraine	0,0442	0,0369	0,0369	0,0000	0,0073
Kosovo (1)	0,0600	0,0556	0,0537	0,0019	0,0044
Serbia	0,0706	0,0589	0,0541	0,0048	0,0117
North Macedonia	0,0783	0,0664	0,0664	0,0000	0,0119
Georgia	0,0809	0,0686	0,0686	0,0000	0,0123
Turkey	0,0847	0,0718	0,0684	0,0034	0,0129
Bosnia and Herzegovina	0,0873	0,0746	0,0729	0,0017	0,0127
Bulgaria	0,0997	0,0831	0,0831	0,0000	0,0166
Montenegro	0,1032	0,0850	0,0834	0,0016	0,0182
Hungary	0,1120	0,0882	0,0882	0,0000	0,0238
Moldova	0,0936	0,0936	0,0936	0,0000	0,0000
Lithuania	0,1255	0,1037	0,0947	0,0090	0,0218
Poland	0,1343	0,1092	0,0884	0,0208	0,0251
Estonia	0,1357	0,1131	0,0982	0,0149	0,0226
Iceland	0,1406	0,1134	0,1112	0,0022	0,0272
Romania	0,1358	0,1141	0,0983	0,0158	0,0217
Croatia	0,1321	0,1169	0,1028	0,0141	0,0152
Malta	0,1305	0,1243	0,1228	0,0015	0,0062
Slovakia	0,1577	0,1314	0,0962	0,0352	0,0263
Slovenia	0,1634	0,1339	0,1125	0,0214	0,0295
Latvia	0,1629	0,1347	0,1136	0,0211	0,0282
Finland	0,1734	0,1398	0,1173	0,0225	0,0336
Czechia	0,1748	0,1444	0,1433	0,0011	0,0304
Greece	0,1650	0,1482	0,1139	0,0343	0,0168
France	0,1765	0,1508	0,1138	0,0370	0,0257
Norway	0,1867	0,1529	0,1360	0,0169	0,0338
Sweden	0,2015	0,1612	0,1297	0,0315	0,0403
Luxembourg	0,1798	0,1666	0,1326	0,0340	0,0132
Austria	0,2034	0,1695	0,1316	0,0379	0,0339
Netherlands	0,2052	0,1708	0,1357	0,0351	0,0344
Portugal	0,2154	0,1751	0,1103	0,0648	0,0403
EU-28	0,2159	0,1854	0,1356	0,0498	0,0305
Cyprus	0,2203	0,1867	0,1762	0,0105	0,0336
Euro area	0,2294	0,1951	0,1404	0,0547	0,0343
Spain	0,2403	0,1986	0,1889	0,0097	0,0417
United Kingdom	0,2122	0,2021	0,1450	0,0571	0,0101
Italy	0,2301	0,2090	0,1432	0,0658	0,0211
Ireland	0,2423	0,2134	0,2027	0,0107	0,0289
Belgium	0,2839	0,2355	0,1965	0,0390	0,0484
Denmark	0,2984	0,2387	0,1084	0,1303	0,0597
Germany	0,3088	0,2595	0,1473	0,1122	0,0493

Calculation Table 5 Cost Variance of electricity produced by small wind turbines per country for the brand vision Air

Vision Air 5 variance cost per wind speed to country prices

Vision Air 5 cost per wind speed				Vision Air 5 Variance to electricity price			
6 m/s	7 m/s	8 m/s	9 m/s	6 m/s	7 m/s	8 m/s	9 m/s
0,3125	0,2273	0,1786	0,1471	-0,2756	-0,1904	-0,1417	-0,1102
0,3125	0,2273	0,1786	0,1471	-0,2588	-0,1736	-0,1249	-0,0934
0,3125	0,2273	0,1786	0,1471	-0,2584	-0,1732	-0,1245	-0,0930
0,3125	0,2273	0,1786	0,1471	-0,2461	-0,1609	-0,1122	-0,0807
0,3125	0,2273	0,1786	0,1471	-0,2441	-0,1589	-0,1102	-0,0787
0,3125	0,2273	0,1786	0,1471	-0,2439	-0,1587	-0,1100	-0,0785
0,3125	0,2273	0,1786	0,1471	-0,2396	-0,1544	-0,1057	-0,0742
0,3125	0,2273	0,1786	0,1471	-0,2294	-0,1442	-0,0955	-0,0640
0,3125	0,2273	0,1786	0,1471	-0,2291	-0,1439	-0,0952	-0,0637
0,3125	0,2273	0,1786	0,1471	-0,2243	-0,1391	-0,0904	-0,0589
0,3125	0,2273	0,1786	0,1471	-0,2241	-0,1389	-0,0902	-0,0587
0,3125	0,2273	0,1786	0,1471	-0,2189	-0,1337	-0,0850	-0,0535
0,3125	0,2273	0,1786	0,1471	-0,2178	-0,1326	-0,0839	-0,0524
0,3125	0,2273	0,1786	0,1471	-0,2163	-0,1311	-0,0824	-0,0509
0,3125	0,2273	0,1786	0,1471	-0,2143	-0,1291	-0,0804	-0,0489
0,3125	0,2273	0,1786	0,1471	-0,2142	-0,1290	-0,0803	-0,0488
0,3125	0,2273	0,1786	0,1471	-0,2097	-0,1245	-0,0758	-0,0443
0,3125	0,2273	0,1786	0,1471	-0,2041	-0,1189	-0,0702	-0,0387
0,3125	0,2273	0,1786	0,1471	-0,2022	-0,1170	-0,0683	-0,0368
0,3125	0,2273	0,1786	0,1471	-0,2013	-0,1161	-0,0674	-0,0359
0,3125	0,2273	0,1786	0,1471	-0,2000	-0,1148	-0,0661	-0,0346
0,3125	0,2273	0,1786	0,1471	-0,1989	-0,1137	-0,0650	-0,0335
0,3125	0,2273	0,1786	0,1471	-0,1987	-0,1135	-0,0648	-0,0333
0,3125	0,2273	0,1786	0,1471	-0,1986	-0,1134	-0,0647	-0,0332
0,3125	0,2273	0,1786	0,1471	-0,1952	-0,1100	-0,0613	-0,0298
0,3125	0,2273	0,1786	0,1471	-0,1897	-0,1045	-0,0558	-0,0243
0,3125	0,2273	0,1786	0,1471	-0,1828	-0,0976	-0,0489	-0,0174
0,3125	0,2273	0,1786	0,1471	-0,1809	-0,0957	-0,0470	-0,0155
0,3125	0,2273	0,1786	0,1471	-0,1799	-0,0947	-0,0460	-0,0145
0,3125	0,2273	0,1786	0,1471	-0,1769	-0,0917	-0,0430	-0,0115
0,3125	0,2273	0,1786	0,1471	-0,1768	-0,0916	-0,0429	-0,0114
0,3125	0,2273	0,1786	0,1471	-0,1765	-0,0913	-0,0426	-0,0111
0,3125	0,2273	0,1786	0,1471	-0,1721	-0,0869	-0,0382	-0,0067
0,3125	0,2273	0,1786	0,1471	-0,1693	-0,0841	-0,0354	-0,0039
0,3125	0,2273	0,1786	0,1471	-0,1692	-0,0840	-0,0353	-0,0038
0,3125	0,2273	0,1786	0,1471	-0,1675	-0,0823	-0,0336	-0,0021
0,3125	0,2273	0,1786	0,1471	-0,1652	-0,0800	-0,0313	0,0002
0,3125	0,2273	0,1786	0,1471	-0,1363	-0,0511	-0,0024	0,0291
0,3125	0,2273	0,1786	0,1471	-0,1236	-0,0384	0,0103	0,0418
0,3125	0,2273	0,1786	0,1471	-0,1160	-0,0308	0,0179	0,0494
0,3125	0,2273	0,1786	0,1471	-0,1098	-0,0246	0,0241	0,0556

Calculation Table 6 Cost Variance of electricity produced by small wind turbines per country for the brand Halo ENERGY

Halo 3.7 variance cost per wind speed to country prices

Halo 3.7 cost per wind speed				Halo 3.7 Variance to electricity price			
6 m/s	7 m/s	8 m/s	9 m/s	6 m/s	7 m/s	8 m/s	9 m/s
0,1955	0,1344	0,1075	0,0860	-0,1586	-0,0975	-0,0706	-0,0491
0,1955	0,1344	0,1075	0,0860	-0,1418	-0,0807	-0,0538	-0,0323
0,1955	0,1344	0,1075	0,0860	-0,1414	-0,0803	-0,0534	-0,0319
0,1955	0,1344	0,1075	0,0860	-0,1291	-0,0680	-0,0411	-0,0196
0,1955	0,1344	0,1075	0,0860	-0,1271	-0,0660	-0,0391	-0,0176
0,1955	0,1344	0,1075	0,0860	-0,1269	-0,0658	-0,0389	-0,0174
0,1955	0,1344	0,1075	0,0860	-0,1226	-0,0615	-0,0346	-0,0131
0,1955	0,1344	0,1075	0,0860	-0,1124	-0,0513	-0,0244	-0,0029
0,1955	0,1344	0,1075	0,0860	-0,1121	-0,0510	-0,0241	-0,0026
0,1955	0,1344	0,1075	0,0860	-0,1073	-0,0462	-0,0193	0,0022
0,1955	0,1344	0,1075	0,0860	-0,1071	-0,0460	-0,0191	0,0024
0,1955	0,1344	0,1075	0,0860	-0,1019	-0,0408	-0,0139	0,0076
0,1955	0,1344	0,1075	0,0860	-0,1008	-0,0397	-0,0128	0,0087
0,1955	0,1344	0,1075	0,0860	-0,0993	-0,0382	-0,0113	0,0102
0,1955	0,1344	0,1075	0,0860	-0,0973	-0,0362	-0,0093	0,0122
0,1955	0,1344	0,1075	0,0860	-0,0972	-0,0361	-0,0092	0,0123
0,1955	0,1344	0,1075	0,0860	-0,0927	-0,0316	-0,0047	0,0168
0,1955	0,1344	0,1075	0,0860	-0,0871	-0,0260	0,0009	0,0224
0,1955	0,1344	0,1075	0,0860	-0,0852	-0,0241	0,0028	0,0243
0,1955	0,1344	0,1075	0,0860	-0,0843	-0,0232	0,0037	0,0252
0,1955	0,1344	0,1075	0,0860	-0,0830	-0,0219	0,0050	0,0265
0,1955	0,1344	0,1075	0,0860	-0,0819	-0,0208	0,0061	0,0276
0,1955	0,1344	0,1075	0,0860	-0,0817	-0,0206	0,0063	0,0278
0,1955	0,1344	0,1075	0,0860	-0,0816	-0,0205	0,0064	0,0279
0,1955	0,1344	0,1075	0,0860	-0,0782	-0,0171	0,0098	0,0313
0,1955	0,1344	0,1075	0,0860	-0,0727	-0,0116	0,0153	0,0368
0,1955	0,1344	0,1075	0,0860	-0,0658	-0,0047	0,0222	0,0437
0,1955	0,1344	0,1075	0,0860	-0,0639	-0,0028	0,0241	0,0456
0,1955	0,1344	0,1075	0,0860	-0,0629	-0,0018	0,0251	0,0466
0,1955	0,1344	0,1075	0,0860	-0,0599	0,0012	0,0281	0,0496
0,1955	0,1344	0,1075	0,0860	-0,0598	0,0013	0,0282	0,0497
0,1955	0,1344	0,1075	0,0860	-0,0595	0,0016	0,0285	0,0500
0,1955	0,1344	0,1075	0,0860	-0,0551	0,0060	0,0329	0,0544
0,1955	0,1344	0,1075	0,0860	-0,0523	0,0088	0,0357	0,0572
0,1955	0,1344	0,1075	0,0860	-0,0522	0,0089	0,0358	0,0573
0,1955	0,1344	0,1075	0,0860	-0,0505	0,0106	0,0375	0,0590
0,1955	0,1344	0,1075	0,0860	-0,0482	0,0129	0,0398	0,0613
0,1955	0,1344	0,1075	0,0860	-0,0193	0,0418	0,0687	0,0902
0,1955	0,1344	0,1075	0,0860	-0,0066	0,0545	0,0814	0,1029
0,1955	0,1344	0,1075	0,0860	0,0010	0,0621	0,0890	0,1105
0,1955	0,1344	0,1075	0,0860	0,0072	0,0683	0,0952	0,1167

Calculation Table 7 Cost Variance of electricity produced by small wind turbines per country for the brand KLIUX

Kliux Geo 1800 variance cost per wind speed to country prices

Kliux Geo 1800 cost per wind speed				Kliux Geo 1800 Variance to electricity price			
6 m/s	7 m/s	8 m/s	9 m/s	6 m/s	7 m/s	8 m/s	9 m/s
0,1973	0,1848	0,1712	0,1559	-0,1604	-0,1479	-0,1343	-0,1190
0,1973	0,1848	0,1712	0,1559	-0,1436	-0,1311	-0,1175	-0,1022
0,1973	0,1848	0,1712	0,1559	-0,1432	-0,1307	-0,1171	-0,1018
0,1973	0,1848	0,1712	0,1559	-0,1309	-0,1184	-0,1048	-0,0895
0,1973	0,1848	0,1712	0,1559	-0,1289	-0,1164	-0,1028	-0,0875
0,1973	0,1848	0,1712	0,1559	-0,1287	-0,1162	-0,1026	-0,0873
0,1973	0,1848	0,1712	0,1559	-0,1244	-0,1119	-0,0983	-0,0830
0,1973	0,1848	0,1712	0,1559	-0,1142	-0,1017	-0,0881	-0,0728
0,1973	0,1848	0,1712	0,1559	-0,1139	-0,1014	-0,0878	-0,0725
0,1973	0,1848	0,1712	0,1559	-0,1091	-0,0966	-0,0830	-0,0677
0,1973	0,1848	0,1712	0,1559	-0,1089	-0,0964	-0,0828	-0,0675
0,1973	0,1848	0,1712	0,1559	-0,1037	-0,0912	-0,0776	-0,0623
0,1973	0,1848	0,1712	0,1559	-0,1026	-0,0901	-0,0765	-0,0612
0,1973	0,1848	0,1712	0,1559	-0,1011	-0,0886	-0,0750	-0,0597
0,1973	0,1848	0,1712	0,1559	-0,0991	-0,0866	-0,0730	-0,0577
0,1973	0,1848	0,1712	0,1559	-0,0990	-0,0865	-0,0729	-0,0576
0,1973	0,1848	0,1712	0,1559	-0,0945	-0,0820	-0,0684	-0,0531
0,1973	0,1848	0,1712	0,1559	-0,0889	-0,0764	-0,0628	-0,0475
0,1973	0,1848	0,1712	0,1559	-0,0870	-0,0745	-0,0609	-0,0456
0,1973	0,1848	0,1712	0,1559	-0,0861	-0,0736	-0,0600	-0,0447
0,1973	0,1848	0,1712	0,1559	-0,0848	-0,0723	-0,0587	-0,0434
0,1973	0,1848	0,1712	0,1559	-0,0837	-0,0712	-0,0576	-0,0423
0,1973	0,1848	0,1712	0,1559	-0,0835	-0,0710	-0,0574	-0,0421
0,1973	0,1848	0,1712	0,1559	-0,0834	-0,0709	-0,0573	-0,0420
0,1973	0,1848	0,1712	0,1559	-0,0800	-0,0675	-0,0539	-0,0386
0,1973	0,1848	0,1712	0,1559	-0,0745	-0,0620	-0,0484	-0,0331
0,1973	0,1848	0,1712	0,1559	-0,0676	-0,0551	-0,0415	-0,0262
0,1973	0,1848	0,1712	0,1559	-0,0657	-0,0532	-0,0396	-0,0243
0,1973	0,1848	0,1712	0,1559	-0,0647	-0,0522	-0,0386	-0,0233
0,1973	0,1848	0,1712	0,1559	-0,0617	-0,0492	-0,0356	-0,0203
0,1973	0,1848	0,1712	0,1559	-0,0616	-0,0491	-0,0355	-0,0202
0,1973	0,1848	0,1712	0,1559	-0,0613	-0,0488	-0,0352	-0,0199
0,1973	0,1848	0,1712	0,1559	-0,0569	-0,0444	-0,0308	-0,0155
0,1973	0,1848	0,1712	0,1559	-0,0541	-0,0416	-0,0280	-0,0127
0,1973	0,1848	0,1712	0,1559	-0,0540	-0,0415	-0,0279	-0,0126
0,1973	0,1848	0,1712	0,1559	-0,0523	-0,0398	-0,0262	-0,0109
0,1973	0,1848	0,1712	0,1559	-0,0500	-0,0375	-0,0239	-0,0086
0,1973	0,1848	0,1712	0,1559	-0,0211	-0,0086	0,0050	0,0203
0,1973	0,1848	0,1712	0,1559	-0,0084	0,0041	0,0177	0,0330
0,1973	0,1848	0,1712	0,1559	-0,0008	0,0117	0,0253	0,0406
0,1973	0,1848	0,1712	0,1559	0,0054	0,0179	0,0315	0,0468

Calculation Table 8 Cost of electricity per windspeed for HALO brand

5% Halo

Year		1	2	3	4	5	6	7	8	9	20
	13000	650	650	650	650	650	650	650	650	650	650
	5.019,13 €										
Capital		650	650	650	650	650	650	650	650	650	650
Interest											
Maintenance		1950	1950	1950	1950	1950	1950	1950	1950	1950	1950
Labor		150	150	150	150	150	150	150	150	150	150
Total cost		2750	2750	2750	2750	2750	2750	2750	2750	2750	2750
	6	11.000	11000	11000	11000	11000	11000	11000	11000	11000	11000
	7	16.000	16000	16000	16000	16000	16000	16000	16000	16000	16000
	8	20.000	20000	20000	20000	20000	20000	20000	20000	20000	20000
	9	25.000	25000	25000	25000	25000	25000	25000	25000	25000	25000
Cost Euro/kWh											
	6	0,250	0,250	0,250	0,250	0,250	0,250	0,250	0,250	0,250	0,250
	7	0,172	0,172	0,172	0,172	0,172	0,172	0,172	0,172	0,172	0,172
	8	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138
	9	0,110	0,110	0,110	0,110	0,110	0,110	0,110	0,110	0,110	0,110

Calculation Table 9 Cost of electricity per windspeed for Kliux brand

5% Kliux

Year		1	2	3	4	5	6	7	8	9	20
	7000	350	350	350	350	350	350	350	350	350	350
	2.702,61 €										
Capital		350	350	350	350	350	350	350	350	350	350
Interest											
Maintenance		1050	1050	1050	1050	1050	1050	1050	1050	1050	1050
Labor		150	150	150	150	150	150	150	150	150	150
Total cost		1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
	6	6.334	6334	6334	6334	6334	6334	6334	6334	6334	6334
	7	6.765	6765	6765	6765	6765	6765	6765	6765	6765	6765
	8	7.303	7303	7303	7303	7303	7303	7303	7303	7303	7303
	9	8.018	8018	8018	8018	8018	8018	8018	8018	8018	8018
Cost Euro/kWh											
	6	0,245	0,245	0,245	0,245	0,245	0,245	0,245	0,245	0,245	0,245
	7	0,229	0,229	0,229	0,229	0,229	0,229	0,229	0,229	0,229	0,229
	8	0,212	0,212	0,212	0,212	0,212	0,212	0,212	0,212	0,212	0,212
	9	0,193	0,193	0,193	0,193	0,193	0,193	0,193	0,193	0,193	0,193

Calculation Table 10 Cost of electricity per windspeed for Vision brand

	5%	Vision									
Year		1	2	3	4	5	6	7	8	9	20
	7000	350	350	350	350	350	350	350	350	350	350
	2.702,61 €										
	4637,5	367,5	385	402,5	420	437,5	455	472,5	490	507,5	700
	3.499,08 €										
Capital		350	350	350	350	350	350	350	350	350	350
Interest											
Maintenance		1050	1050	1050	1050	1050	1050	1050	1050	1050	1050
Labor		150	150	150	150	150	150	150	150	150	150
Total cost		1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
	6	4.000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	7	5.500	5500	5500	5500	5500	5500	5500	5500	5500	5500
	8	7.000	7000	7000	7000	7000	7000	7000	7000	7000	7000
	9	8.500	8500	8500	8500	8500	8500	8500	8500	8500	8500
Cost Euro/kWh											
	6	0,388	0,388	0,388	0,388	0,388	0,388	0,388	0,388	0,388	0,388
	7	0,282	0,282	0,282	0,282	0,282	0,282	0,282	0,282	0,282	0,282
	8	0,221	0,221	0,221	0,221	0,221	0,221	0,221	0,221	0,221	0,221
	9	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182	0,182
	6.421,35 €										
	7.000,00 €		270,42 €								
	350,00 €										
	1	350	17,5								
	2	350									
	3	350									
	4	350									
	5	350									
	6	350									
	7	350									

Calculation Table 11 Calculation data and results for implementation of SWTs on Vienna's flat roofs

Data

Number of buildings	165.000	Data from Wien in zahlen
Pct of buildings used for air turbines	20%	Buildings with flat roofs, data derived from stadt wien and Dang diss
Number of useful buildings	11.000	Assumption 1/3 usable
Total gross electricity consumption MWh	3.654.000	Data from Energieflussbild from stadt wien
Space per wind turbine based on diameter sq. meters	15	Installation on post, limitation due to blade diameter
Average surface of roofs per building sq. meters	321	
Number wind turbines per building (max)	21	
Max number of wind turbines in Vienna	235.400	
Total surface of roofs sq. meters	52.965.000	Number in accordance to stadt wien's number; 53 km2 roof surface
HALO 3.7 annual output with 5m/sec speed	7.000	
Number of wind turbines to cover Vienna demand	522.000	
Average number of wind turbines per building to cover deman	16	
Total output of wind turbines MWh	1.647.800	
Percentage coverage of Vienna demand max number of turbi	45,10%	
Weight of each turbine (kg)	375	
Investment per each turbine (Euros)	13.000	

Number of wind turbines per building	Used sq. meters of each roof	Added weight per building in tons	Total annual output MWh	Pct coverage of annual demand	Total number of wind turbines	Total investment million Euros
3	45	1,13	231.000	6,32%	33.000	429,00
6	90	2,25	462.000	12,64%	66.000	858,00
9	135	3,38	693.000	18,97%	99.000	1.287,00
12	180	4,50	924.000	25,29%	132.000	1.716,00
15	225	5,63	1.155.000	31,61%	165.000	2.145,00
18	270	6,75	1.386.000	37,93%	198.000	2.574,00
21	315	7,88	1.617.000	44,25%	231.000	3.003,00