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Urban Wind Energy Production Potential: New Opportunities

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Summary:

Climate policy challenges reinforce the search for additional elements of renewable energy generation. Small-scale wind energy provides new opportunities for decentralized electricity production, while avoiding grid-dependence and transmission losses. This paper presents a potential analysis for urban wind energy production for two European cities and one US-American city. The simulation follows the framework presented by Rezaeiha et al. (2020) and extends it by using the reanalysis wind grid dataset MERRA2 by NASA (GES DISC, 2020). The dataset combines reliable and complete weather observations in a standardized manner on a global scale, mitigating observation gaps of meteorological stations. This allows us to provide a preliminary potential analysis, that can be applied to almost any city worldwide. The analyzed cities show considerable urban wind energy farming potential. For the city of Lisbon, Portugal, the installation of seven VAWT on 264 buildings between 20-115 m throughout the city provides an annual wind energy production potential (AEPP) of 17,046 MWh, which approximately corresponds to the annual electricity consumption of 13,275 residents. In Hamburg, Germany, the AEPP amounts to 38,883 MWh produced by 4,970 turbines (seven turbines on 710 buildings), which approximately corresponds to the annual electricity consumption of 38,883 residents. In Boston, Massachusetts, USA seven turbines on 671 buildings between 20-220 m yield an AEPP of 29,171 MWh, which covers the annual electricity consumption of 6,400 residents. Individual insights for each city can be derived from this analysis, such that a general direction of thrust for the expansion of urban wind energy in a city can be derived. Additionally, the AEEP can easily be increased by using more efficient HAWT, whereby technological advancements in recent years have made them applicable even for the urban environment setting.

<u>Zusammenfassung:</u>

Klimapolitische Herausforderungen verstärken die Suche nach zusätzlichen Elementen der erneuerbaren Energieerzeugung. Windenergie in kleinem Maßstab bietet neue Möglichkeiten zur dezentralen Stromerzeugung, während gleichzeitig Netzabhängigkeit und Übertragungsverluste vermieden werden. Dieses Papier präsentiert eine Potenzialanalyse für die urbane Windenergieproduktion für zwei europäische Städte und eine US-amerikanische Stadt. Die Simulation folgt dem von Rezaeiha et al. (2020) vorgestellten Rahmen und erweitert diesen durch die Verwendung des Reanalyse-Windnetz-Datensatzes MERRA2 der NASA (GES DISC, 2020). Der Datensatz vereint zuverlässige und vollständige Wetterbeobachtungen in standardisierter Weise auf globaler Ebene und mildert Beobachtungslücken meteorologischer Stationen. Dies ermöglicht uns eine vorläufige Potenzialanalyse, die auf nahezu jede Stadt weltweit angewendet werden kann. Die analysierten Städte zeigen ein beträchtliches Potenzial für die urbane Windenergienutzung. Für die Stadt Lissabon, Portugal, ergibt sich durch die Installation von sieben VAWT auf 264 Gebäuden zwischen 20 115 m im gesamten Stadtgebiet ein jährliches Windenergie-Erzeugungspotenzial (AEPP) von 17.046 MWh, was in etwa dem jährlichen Stromverbrauch von 13.275 Einwohnern entspricht. In Hamburg, Deutschland, beträgt das AEPP 38.883 MWh, produziert von 4.970 Turbinen (sieben Turbinen auf 710 Gebäuden), was ungefähr dem jährlichen Stromverbrauch von 38.883 Einwohnern entspricht. In Boston, Massachusetts, USA ergeben sieben Turbinen auf 671 Gebäuden zwischen 20 220 m ein AEPP von 29.171 MWh, was dem jährlichen Stromverbrauch von 6.400 Einwohnern entspricht. Aus dieser Analyse lassen sich individuelle Erkenntnisse für jede Stadt ableiten, so dass eine generelle Stoßrichtung für den Ausbau der urbanen Windenergie in einer Stadt abgeleitet werden kann. Zusätzlich kann der AEEP durch den Einsatz effizienterer HAWT leicht erhöht werden, wobei die technologischen Fortschritte der letzten Jahre diese auch für den städtischen Bereich einsetzbar gemacht haben.

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Table of Contents

List of Figures

List of Tables

1. Introduction

The expansion of renewable energy in G20 countries and beyond is crucial for achieving the ambitious goal of the Paris Agreement to mitigate the global average temperature increase to below 2°C above pre-industrial levels (United Nations, 2015). The European Union (EU) recommitted itself to the agreement by passing the European Green Deal, aiming to become the first climate-neutral continent by 2050 (European Commission, 2019). In response to the economic recession due to the Covid-19 pandemic, the European Commission increased its commitment appropriations of the multiannual financial framework for the years 2021 to 2027 by €750 billion (NextGeneration EU), assigning €10 billion to the Just Transition Fund. This fund supports environmentally-friendly investments and is further strengthened by €40billion of external revenue from the European Recovery Instrument. EU member states could use this opportunity to strengthen the economy with new perspectives for renewable energy production.

A key driver of achieving climate-neutrality in the upcoming decades, is the replacement of CO2-emission intensive technologies with clean alternatives, especially in the generation of electricity from renewable sources. The expansion of renewable energy will depend on political goals set through national and international climate policy. However, relative CO2 emission prices and (endogenous) technological progress will also play a role, as well as shifts in private preferences in favor of a more sustainable lifestyle.

In 2019, approximately one third of the globally-generated electricity came from renewable energy sources (IRENA, 2019). Half of the renewably generated electricity was produced by hydropower plants, while wind and solar energy accounted for most of the remainder (IRENA, 2019). In the EU, 40 % of the consumed electricity came from renewable sources, of which 13% was produced by hydropower plants, 11% by wind turbines, 5% by biofuels and 4% by solar power (Eurostat, 2020b). Despite global renewable energy production growing annually by 5.8% on average over the last decade (IRENA, 2020a), the current increase in renewable energy production is not sufficient to achieve climate-neutrality by 2020 (Welfens, 2019).

As regards climate neutrality challenges, it is clear that the relative cost development dynamics of renewable energy – compared to fossil fuels – will be a decisive element for the composition of new energy investment. According to IRENA (IRENA, 2020b), for 2019, 72% of new capacity installments worldwide represented renewables; in the period 2010-2019 the worldwide weighted-average levelized cost of electricity (LCOE) of solar photovoltaics (PV) reduced by 82% whereas that of concentrated solar power (CSP) reduced by 47%; onshore wind and offshore wind by 39% and 29%, respectively. Note that LCOE refers to a life cycle discounted cost concept. Solar PV electricity costs reduced by 13% in 2019 compared to the year before and reached $0.068 per kWh. Looking at the new energy projects commissioned in 2019, the worldwide weighted-average LCOE of offshore and onshore wind energy both reduced by about 9% in a year-on-year perspective and stood at $0.053/kWh for onshore wind energy and $0.115/kWh for offshore wind energy. The costs for CSP reduced by 1% to $0.182/kWh. As regards new geothermal power projects, costs are about $0.073/kWh while the weighted-average global costs for hydropower faced an increase from $0.037/kWh in 2010 to $0.047/kWh in 2019. These general international tendencies suggest that renewable energy options will have improving medium perspectives with respect to investment worldwide. There is, however, a special topic that has been little researched, although the economic and climate relevance could be considerable, namely urban wind farming which could be a new crucial niche activity in hundreds of cities worldwide – here, an exemplary focus is placed on Lisbon, Hamburg and Boston, Massachusetts for which simulations are offered for the first time.

In a general perspective, the International Energy Agency (IEA) has been rather optimistic that the rise of the share of renewable energy will globally go on in the medium term and that the long run offshore wind potential will be about 18 times the world demand of 2018 (IEA, 2019). Effectively, the installed wind energy capacity has been increasing annually by 17.8% on average between 2010 and 2018, (IRENA, 2020a). However, the actual global wind energy generation in 2018 was only 0.3% of global annual demand in 2018. Ruiz et al. (2019) find that without changing the current legal requirements for the installation of large wind turbines, the wind potential in the EU is equivalent to three times its current annual electricity demand. This production potential involves the installation of 8,400 TWh worth of onshore wind turbines and 1,300 TWh worth of offshore wind turbines (Ruiz et al., 2019).

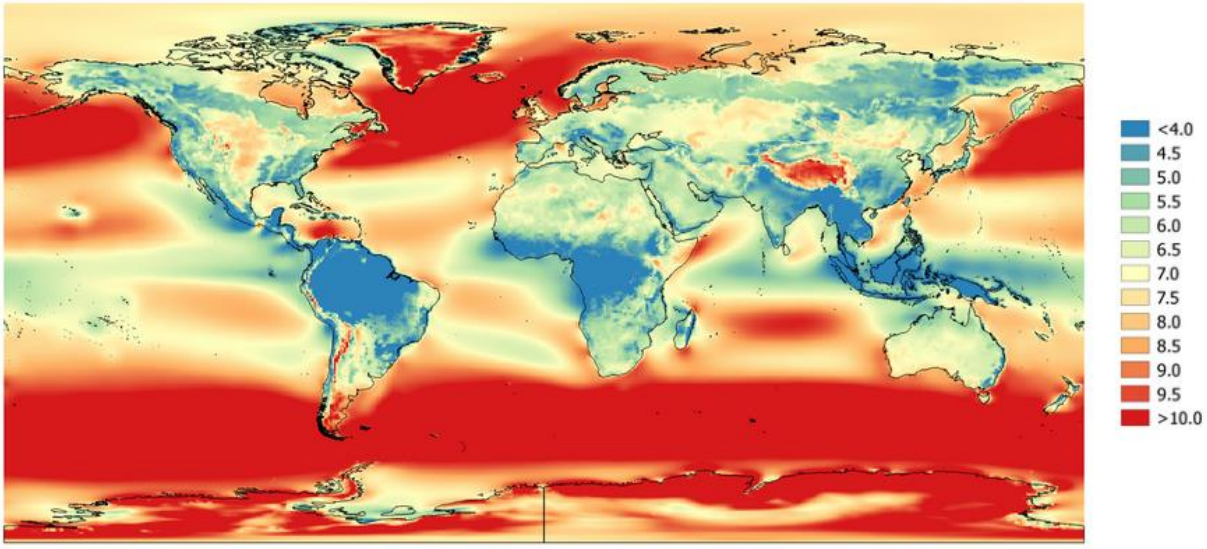
While the expansion of solar energy and off-shore wind energy have been strong pillars of renewable energy in many countries, the expansion of land-based wind energy generation, including the particular form of urban wind farming has not been much considered by policy makers. Although there were early initiatives to consider the role of urban wind electricity generation – including the EU-financed research project WINEUR (Wind Energy Integration in the Urban Environment) (Cace et al., 2007) in which researchers from several EU countries looked into prospects for urban wind turbines, we consider it to be a rather neglected form of renewable electricity. On-site energy production, such as urban wind farming, bypasses the problem of grid extension and transmission losses. The negative impacts of power blackouts due to instable grids, such as frequently occuring in the Gaza region (Elnaggar et al., 2017), could be weakened or even avoided.

Small Wind Turbines (SWTs) are especially interesting for cities with only limited potential for solar energy generation, due to long winters and few hours of sunshine throughout the year. If combined with solar panels they can achieve very good results throughout the whole year. Elnaggar et al. (2017) perform a feasibility study for roof-mounted SWTs in the Gaza region and find great potential for wind exploitation in the densely built region, especially when the turbines are combined with solar panels. Roof-mounted small wind turbines can then compensate for the weakness of photovoltaic energy in winter months (Elnaggar et al., 2017).

Particularly coastal cities might profit from the installation of SWTs. High wind velocities combined with the possibility of installing turbines on already existing high buildings might hold tremendous potential for electricity generation. The global wind potential has been assessed by NASA as part of the global dataset MERRA[1]. Global wind speeds from MERRA have been visualized by the Global Wind Atlas and are displayed in Figure 1 (Global Wind Atlas, 2018) . As expected, onshore wind currents are particularly high in coastal regions.

[1] The MERRA dataset has recently been updated and has been replaced with MERRA2 (NASA, 2019).

Figure 1: Mean wind speed at 110 m from MERRA reanalysis, 1979-2013.



Source: Global Wind Atlas, 2018 (based on NASA (2019))

The following analysis gives at first a brief literature review before we consider the cities of Lisbon, Hamburg and Boston, Massachusetts. Three interesting cases of port cities – with Lisbon representing high wind and solar energy potential, while Hamburg's more northern geographic location makes it more exposed to wind energy than to solar energy sources. Boston has a good exposure to coastal winds and owns considerably more skyscrapers and high-rise buildings than the exemplary European cities. Section 3 treats the methodology for the simulation study, while Section 4 presents the empirical analysis. Section 5 discusses the key findings and Section 6 looks at the policy conclusions and perspectives for further research. At the bottom line there are three crucial findings: a) urban wind farming has an interesting potential which so far has not been exploited; b) different cities require customized approaches for a comprehensive expansion of urban wind energy production; c) the technological progress potential in this nascent technology field seems to be considerable. The economic and ecological benefit arises not just in terms of additional renewable energy but also in avoided investment in grid network. A commercially viable case for urban wind farming may be assumed in most cities close to the seas as well in cities with other favorable geographical positions or urban features.

2. Literature Review

Research on the potential of urban wind energy generation is still relatively scarce, but academic interest in the topic is growing constantly. The most studied topics are the turbulent, random nature of urban wind flows and the technical design of SWTs.

Urban geography and building geometry

The rough urban ground surface creates turbulences, overall unstable and unpredictable wind conditions. Site-specific characteristics, such as wind-shielding constructions or trees, as well as wake effects caused by the installation of multiple turbines must be considered thoroughly before a specific investment project in SWTs is undertaken (WINDExchange, 2020).

Additionally, the natural ground roughness might considerably influence the final overall height of the building and therefore the wind speed at its roof. Since tedious data collection on individual sites is costly, time-consuming and inconvenient for the large-scale assessment of the urban geography and the geometry of buildings, 3D-models pose a next to best approach. They are ideal to take the natural ground roughness in a specific area into account, while also providing geometrical data of existing buildings. However, 3D-models are only provided by some (regional) governments (e.g. the Senate Administration for Urban Development and Housing in Berlin, Germany) or must be bought from private providers (Milojevic-Dupont et al., 2020). Milojevic-Dupont et al. (2020) developed a method to predict building heights based on a machine learning method that is fed with openly available 2D-geometrical data on urban form and a small amount of domain knowledge from the specific study site. The appliance of their method showed very promising results (prediction of building heights with an average error below 2.5 m), although it performed worse for high-rise buildings than for low-rise buildings. Other existing studies assess wind characteristics for rough ground surfaces through digital elevation models (Di Sabatino et al., 2008; Kent et al., 2019), computational fluid dynamic simulations (Simões and Estanqueiro, 2016; Toja-Silva et al., 2018) or LiDAR data (Bonczak and Kontokosta, 2019; von der Grün et al., 2020). Simões et al. (2009) develop a simplified approach to choose adequate locations for SWTs in cities which, however, still seems difficult to apply to a large scale preliminary assessment of urban wind production potential.

Assessing wind speed

Regarding the assessment of wind speeds, some studies apply statistical modelling through Weibull distributions based on historic wind data of varying level of detail (Kassem et al., 2019; Rezaeiha et al., 2020). Some authors use historical observations from local meteorological stations (Rodriguez-Hernandez et al., 2019), however, they are often incomplete or unprecise (Ritter et al., 2015; Ricciardelli et al., 2017). Reanalysis data in grid format - reanalysis means retrospective analysis - can be a convenient way to estimate urban wind production potential as, on the one hand, interpolation to (narrow) grids has already been performed by experts, and on the other hand, reanalysis data avoids data imprecision or lack of completeness. Ritter et al. (2015) use Modern-Era Retrospective Analysis for Research and Applications (MERRA) data from NASA to derive the potential for large-scale wind energy production in Germany. Wilke et al. (2020) use a very narrow national grid dataset to derive the potential for wind energy production through roof installed SWTs in Berlin. Such narrow grid data, however, is not available in most regions. The approach of Rezaeiha et al. (2020) is similar to the work of Wilke et al. (2020). The main difference lies in the assessment of wind characteristics, as Rezaeiha et al. (2020) use average annual wind speed as a function of height instead of grid data. Additionally, Wilke et al. (2020) use coordinates to assign specific buildings to their respective grid cell, while Rezaeiha et al. (2020) estimate Weibull distributions to generate average wind profiles across different locations. Rezaeiha et al. (2020) apply their methodology in a case study for 18 major cities in the Netherlands. They find that a single turbine can generate between 4 and 21 MWh annually depending on the average wind conditions of a building. Wilke et al. (2020) find that if only one SWT was installed on every building that has a sufficiently large roof-surface and is at least 10 m high, almost 5% of the overall household's electricity consumption in Berlin could be covered. If multiple SWTs were installed on these buildings (the amount depends on the specific roof-surface), up to 37% of the household's electricity consumption could be produced. If this self-produced electricity in Berlin was used to replace electricity obtained from the burning of lignite, 91% of lignite-related CO2-emissions could be avoided (not considering CO2 emissions that are generated during the production of the turbines) (Wilke et al., 2020).

Small wind turbines

SWTs can be installed in three different ways in the urban environment (Rezaeiha et al., 2020): a) The stand-alone construction of SWTs next to existing buildings (e.g., in parks or gardens), b) the integration of SWTs into the architecture of the building itself or c) roof-top installation (retrofitted). The choice of the type of turbine should be carefully considered based on the individual location characteristics and wind conditions.

The technological development of SWTs as compared to large wind turbines is still in a fairly early stage (Cace et al., 2007). Even though it is often mentioned that large wind turbines outperform SWTs when it comes to yield-efficiency and investment costs, the conditions under which they run are completely different. It can be expected that the investment costs of SWTs will decrease and their efficiency will increase in the future due to improved research and technical experience from the manufacturers (Cace et al., 2007; Kumar et al., 2018). Kc et al. (2019) provide a review - as of 2018 - of several studies on SWT technology in the built environment and study the performance of a specific SWT in an urban installation setting. Kumar et al. (2018) review research on vertical axis wind turbines (VAWT)[2], also as of 2018. Cace et al. (2007) provide a review of manufacturers from the UK and the Netherlands and compare the technical development of SWTs. The authors recommend that more thorough investigations of urban wind characteristics are performed to adjust SWT design consistently (KC et al., 2019).

Subsequently, we examine the potential role of urban wind farming regarding the usage of roof-mounted wind turbines. Section 3 explains our methodology which is applied in Section 4 to two exemplary cities in the EU, namely Lisbon and Hamburg and one US-American city, namely Boston, Massachusetts.

3. Methodology

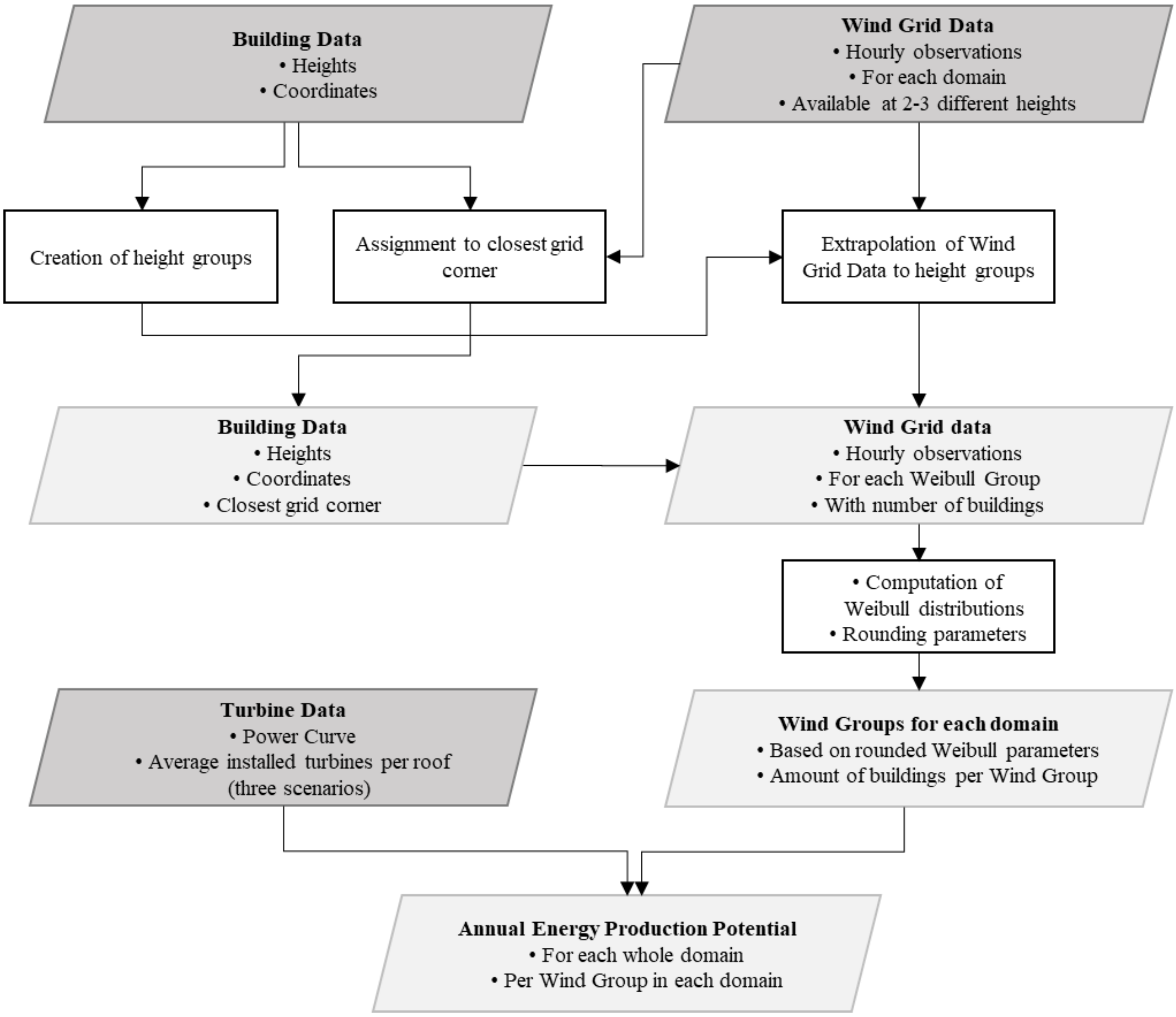
Our methodology follows the framework presented by Rezaeiha et al. (2020) who measure the preliminary, large-scale wind production potential of roof-mounted turbines. Preliminary, comparable simulation results give new insights into the neglected opportunities for the growth of urban wind-based electricity production and hence the role of a new pillar in climate policy. The installation of roof mounted VAWT on a chosen set of existing buildings in an urban environment is simulated. The specific urban study sites (exemplary cities) are referred to as "domains".

The results of this analysis are easily extendable to any city or region worldwide. This is achieved by using globally available reanalysis wind grid data. This is also the main difference to the framework of Rezaeiha et al. (2020). Using reanalysis wind data in grid format allows for a more detailed derivation of the approximate wind speed on individual buildings and provides a broader dataset for the derivation of the Weibull parameters. Since this wind grid

[2] For more information on different types of turbines, see Section 1.3 Turbines.

dataset is available on a global scale, our framework is applicable for any city worldwide. Input data to this analysis are building data, wind speed characteristics and turbine characteristics. A first graphical representation of the methodology is given in Figure 2:

Figure 2: A graphical representation of the framework/methodology



Source: Own representation

3.1 Buildings

In a first step, the potential buildings that enter the analysis, their respective heights and their coordinates must be identified for each city. In the original framework by Rezaeiha et al. (2020) there is no need for specific building coordinates, as no wind grid data is used.

The benchmark for buildings that are chosen as eligible for entering the analysis is set based on their potential for efficient wind harvesting. Only buildings that are not substantially overshadowed by other buildings should enter the analysis. For a preliminary estimation of wind potential, a minimum building height can serve as an easily determined benchmark. This benchmark building height can be chosen based on the average height of buildings in a city. Buildings are then sorted into height groups and a reference height H_r for each height group is defined, which in this paper will be the average of the upper and lower bound of the height group. Later, the reference height will be used to assign the annual mean wind speed distribution to each height group.

If available, the average roof-surface of these buildings might be used to determine an average number of turbines that are to be installed. However, this information can often not be easily obtained for a large set of buildings. In order to simplify the large-scale analysis, an assumption about the average number of turbines per buildings can be made.

Assignment of buildings to the closest grid-corner of the wind dataset
Different to the original framework, this paper uses reanalysis wind grid data for the assessment of wind characteristics. Reanalysis grid data provides wind speed (and direction) observations for each corner of each raster quadrant.

Each building in the dataset must be assigned to its closest grid corner to refer it to the wind speed that is most closely related to the real wind speed on the roof-top of this specific building. The wind observations at each grid corner are than extrapolated to the reference height of each height group, such that a Weibull distribution can be measured for each height group. Detailed explanation is given in the next section.

3.2 Wind

The annual wind speed distribution, as well as the average annual number of hours as a function of annual average wind speed can be obtained by fitting a Weibull distribution to hourly wind data and averaging it over a period of 10-30 years (Rodriguez-Hernandez et al., 2019; Rezaeiha et al., 2020). The two-parameter Weibull probability density function w(U) is displayed in equation (1).

$$w(U) = \frac{k}{A}\left(\frac{U}{A}\right)^{k-1} e^{-\left(\frac{U}{A}\right)^{k}} \quad (1)$$

The Weibull distribution has two parameters, namely the scale parameter A and the shape parameter k. The larger k is, the sharper the distribution, which indicates less variance around the mean wind speed. U is the mean annual wind speed and e is Euler's number.

The respective Weibull cumulative density function W(U) is displayed in equation (2).

$$W(U) = 1 - e^{-\left(\frac{U}{A}\right)^k} \tag{2}$$

The Weibull distribution is computed from the reanalysis wind data for every grid corner in every studied city and each height group. These groups will be referred to as Weibull-groups. For example, if there is one city to be studied that is comprised of one grid quadrant, then there are four grid corner points with hourly observations for each. Assuming that there are 15 height groups (previously defined by through the building data set), then there are 60 $(4 * 15)$ Weibull groups. A Weibull distribution function is computed for each, such that every Weibull group has individual shape and scale parameters. With the scale and shape parameters from a fitted Weibull distribution, the mean wind speed can be derived through equation (3) by mean of the gamma function Γ:

$$U = A * \Gamma\left(1 + \frac{1}{k}\right) \tag{3}$$

If no hourly wind speed observations over a long time-horizon are available, but only an annual mean wind speed, then the annual mean wind speed and variance can be used instead to derive the Weibull parameters. Rezaeiha et al. (2020) use this quality of the Weibull distribution for their case study in the Netherlands.

3.2.1 Vertical extrapolation of wind speed

Since each Weibull group needs a Weibull distribution, the available wind grid data in each grid corner point might have to be extrapolated to the reference heights H_r of the previously defined height groups. The number of extrapolation processes and the extrapolation distance depends on the available heights in the wind grid dataset used. Reanalysis wind data in grid format is normally provided for different heights; however, wind speed might not be available for all reference heights. Vertical extrapolation of wind data is typically performed with either the power law approach or the logarithmic law. Gualtieri/Secci (2012) find, that the power law yields an "*accurate and better representation of wind speed profiles*" (Gualtieri and Secci, 2012) than the logarithmic model, at least under unstable and neutral conditions. The power law (4) is also easy to apply as it only has one unknown parameter, namely the wind shear coefficient α.

$$v_r = v_b * \left(\frac{H_r}{H_b}\right)^{\alpha}, \text{ where } H_r > H_b \tag{4}$$

The power law computes the specific wind speed v_r at reference height H_r. For this purpose, the wind speed v_b at the baseline height H_b is needed, as well as the wind shear coefficent α. As an example, assume the wind grid dataset provides wind measurements at a height of 10 m which should be extrapolated to 20 m, then $H_b = 10$ and $H_r = 20$. The wind shear coefficient α relates to the intensity of turbulence at the studied site. The amount of turbulence is important, especially in the urban environment and affects the productivity of wind turbines as well as their lifetime (Manwell et al., 2011). The coefficient can be easily derived, based on equation (4), if wind speeds at two different heights are available.

$$\alpha = \frac{\ln(v_2) - \ln(v_1)}{\ln(H_2) - \ln(H_1)} \tag{5}$$

If wind measurements at only one height are available, then the wind shear coefficient can either be approximated through the power law "rule of thumb" (Gualtieri and Secci, 2012; Elnaggar et al., 2017), assuming that $\alpha = {}^{1}/_{7}$, or through approaches that include the roughness length of the ground[3] (Gualtieri and Secci, 2011; Wilke et al., 2020). Note that the roughness of the ground, expressed through the parameter "roughness length", might considerably influence the real height of a building and therefore the real wind speed at its roof top. If narrow roughness length and wind speed data are available, then the WSC α should be calculated individually for each datapoint.

After each height group being assigned an individual wind dataset with hourly observations at each subdomain, then the computation of a Weibull distribution for each Weibull group is possible. The resulting Weibull-parameters are rounded, such that it becomes viable to aggregate the Weibull groups to wind groups if they have similar shape and scale parameters.

From the Weibull cumulative density function (equation (2)), the average annual number of hours as a function of annual average wind speed can be derived for specific wind bins and each wind group, as shown in equation (6), with 8760 representing the numbers of hours of one year. U_{j+1} is the upper bound of the wind speed bin and U_j is the lower bound.

$$h(U) = 8760 * \left(w(U_{j+1}) - w(U_j)\right) \tag{6}$$

[3] The roughness length of the ground is defined approximately as one-tenth of the average height of surface roughness elements (buildings, trees, etc.) WMO (2008).

3.2.2 Wind groups for each domain and assignment of buildings

Each building has been assigned to its closest grid-corner and is consequently assigned to a Weibull-group. From the derivation of the Weibull parameters for each Weibull-group, buildings with similar Weibull parameters can now easily be allocated in a wind group, almost independently of their location.

The construction of wind groups is a special feature of the approach of Rezaeiha et al. (2020). Their simplified approach to assess wind speeds in the turbulent urban environment avoids the unsatisfying assignment of wind-speeds depending on geographical features, but groups buildings (almost) independently of their location by generalizing wind conditions. The addition of reanalysis wind grid data to their approach adds more accuracy, as buildings are initially assigned to their closest grid corner before being put into wind groups. In this approach each domain is assigned an own array of wind groups since the exemplary cities are geographically much more distant to each other than the studied cities in the approach of Rezaeiha et. al (2020), who focused on cities in the Netherlands.

3.3 Turbine

This analysis studies the potential of roof top installed SWTs in the urban environment. Roof mounted turbines are especially interesting in cities as this installation method does not require additional space – a very limited resource in densely populated areas. Furthermore, buildings provide an already existing “tower”-structure for the turbines, such that better wind conditions in higher altitudes can be used without further construction.

The rated capacity, or nominal power, is typically used to categorize wind turbines. It is the production output that a turbine produces under optimal (very strong) wind conditions. Even though it is not a good indicator for the average level of production under normal wind conditions, the rated capacity serves as grouping-benchmark. The categorization of wind turbines into small and large wind turbines is however not consistent (BWE, 2011; Tummala et al., 2016; Rezaeiha et al., 2020). The German Wind Energy association (BWE) provides an overview of the international categorizations of SWTs[4] and develops a definition of categories for SWTs based on an international comparison (BWE, 2011). Accordingly, SWTs that are applicable for roof top installation generally have a rated capacity of 1.5-5 kW and are considered micro-turbines (a sub-class of SWTs) (BWE, 2011). They can either be installed in an off-grid system, where all energy produced is consumed or stored at the site of production, or as an integrated system, where excess-energy is fed into the grid.

There are two main types of SWTs (Cace et al., 2007). Horizontal axis wind turbines (HAWTs) have a rotor shaft that lies horizontally to the wind, while vertical axis wind turbines (VAWT)

[4] The report is based on categorizations of the British Wind Energy Association (BWEA), the American Wind Energy Association (AWEA) and the European Wind Energy Association (EWEA, now: WindEurope) (BWE (2011)).

rotate perpendicular to the wind. HAWTs are widely applied in offshore and onshore wind farms and their technical development is more mature as compared to VAWT. HAWTs are found to produce energy much more efficiently under steady wind flows (Cace et al., 2007; Johari et al., 2018). However, VAWT are more suitable for the urban environment, as they do not require steady wind streams and even profit from highly turbulent and skewed winds (Mithraratne, 2009; Toja-Silva et al., 2013; Battisti et al., 2018; Johari et al., 2018) and cope relatively well with weak or unstable wind conditions (Battisti et al., 2018; Kumar et al., 2018). Fazlizan et al. (2019) find that VAWT generate a higher output under skewed wind flows than HAWT and even perform better in skewed than in normal wind flows. Skewed wind flows are common in the urban environment as wind flows are diverted by many obstacles. VAWT can often be installed on the roof-top of existing buildings, such that no additional space is consumed. VAWT also produce lower noise levels than HAWTs (Cace et al., 2007; Battisti et al., 2018) and are less visually intrusive (Cace et al., 2007).

There are two main types of VAWT, specified by their rotor types: The Darrieus rotor VAWT and the Savonius rotor VAWT. The Savonius rotor works drag-based and is normally used for purposes with very low energy demand, such as small pumping systems or rotating advertisements (BWE, 2020). Under its drag-based system, the wind pushes the blades such that the rotation speed is always lower than the wind speed (Cace et al., 2007). The traditional Darrieus rotor has curved blades and works lift-based, which makes it possible for the rotor to spin faster than the wind speed (Cace et al., 2007). Therefore, the Darrieus-rotor produces energy more efficiently than the Savonius rotor (Cace et al., 2007; BWE, 2020). Variations of the original Darrieus rotor that perform more efficiently than the traditional form are the H-Darrieus rotor with straight blades (BWE, 2020; Jüttemann, 2020) and the helical VAWT (Rezaeiha et al., 2020). Both lastly mentioned rotor types should be considered when selecting a specific roof installed VAWT for the urban environment. Figure 3 displays a helical VAWT (A) and a H-Darrieus rotor VAWT (B) that are currently available on the market.

Figure 3: Vertical Axis Wind Turbines (VAWT)

Source: A - Helical VAWT (Turby by Turby b.v. (www.turby.nl)). B - H-Darrieus rotor VAWT (Aeolos 1kW by Aelos (https://www.windturbinestar.com))

There are also some manufacturers who experiment with other types of SWT, such as the modification of a HAWT, called Energy Ball (C), also known as Venturi-wind-turbine (Cace et al., 2007; Elshazly et al., 2019), or a modified VAWT (D), that is currently being developed by the Complutense University of Madrid and supported by the Horizon 2020 program of the European Commission (European Commission, 2020b). Both innovations are stated to be applicable for roof-top installation and operation in the urban area (European Commission, 2020b; Cace et al., 2007) (see Figure 4). It should also be noted that most recent technological developments in the urban wind sector includes HAWT as well. In its sector monitor for 2020, the German Wind Energy Agency (BWE) recommends only one wind turbine that is applicable for roof-installation in the urban environment: A small, modular HAWT from the Berlin start-up MOWEA (E) (BWE, 2019). Even though the rated capacity of a single MOWEA turbine is quite small (0.5 kW), the turbine is designed for modular assembling of multiple turbines, both vertically and horizontally.

Figure 4: Further models of Small Wind Turbines

Source: Energy Ball (C) (Cace et al., 2007). EOLI FPS wind turbine (D) (European Commission, 2020b). MOWEA wind turbine (E) (BWE, 2019)

For this framework, the power curve of the exemplary turbine that is chosen for the analysis is needed. The power curve describes the energy output of a turbine depending on the wind speed that enters the turbine and is typically provided by the manufacturer. If the power curve is not available, it can, for instance, also be obtained through computational fluid dynamics (Simões and Estanqueiro, 2016; Toja-Silva et al., 2018).

Additionally, the number of turbines on each building must be determined. The maximum number of turbines that can be installed on a building is mainly influenced by the roof-surface, the width of the turbine and the safety distance that must maintained between turbines. Additionally, especially for real-world installation analysis, one should consider static aspects of the building structure and, where applicable, the wake effect between turbines as well as the optimal positioning towards the main direction of wind.

3.4 Wind energy potential

The annual wind energy potential is calculated for each domain and, more detailed, for each height group in each domain. This gives preliminary insights into the wind energy potential of a whole domain and additionally into the production potential of specific height groups. It also allows for the comparison of the production potential of height groups among domains.

It should be considered that turbines have a mutual influence on their energy output, when installed closely to each other. A turbine processing wind from the front will create a trail of turbulence and slow down the wind behind itself (wake). This wake effect causes turbines that are installed too close to each other not to receive full wind input. Corscadden et al. (2013) observe a reduction of the power output of small horizontal turbines of 25% 5.7 diameters downwind. Bayeul-Lainè et al. (2013) find, that the power coefficient[5] of VAWT in a linear positioning is reduced by 18-72% as compared to a triangular positioning. Rezaeiha et al. (2020) use the coefficient $C_W = 0.88$ to account for the mutual influence of closely installed VAWT. Their coefficient is based on a study by Sahebzadeh et al. (2020) and derived as described here: *"The coefficient is estimated based on an extensive number of high-fidelity CFD simulations for a dual array of turbines with various relative spacing (distance within 1.25d to 10d [d: turbine diameter], angles within −90° to 90°) and different relative rotational directions (co- and counter-rotating)*" (Rezaeiha et al., 2020). This approach uses the same wake coefficient as Rezaeiha et al. (2020), namely $C_W = 0.88$. The annual wind energy potential ($AEPP_{total,j}$) for a domain d can therefore calculated as displayed in equation (7):

$$AEPP_{d,total} = C_W * \sum_{i=1}^{N} AEPP_{d,total,i} \tag{7}$$

$AEPP_{d,total,i}$ is the total annual wind energy production potential of wind group i in domain d. NB_i is the number of buildings per wind group i and NT is the average number of turbines that are installed on each building. The derivation of $AEPP_{d,total,i}$ is shown in equation (8).

$$AEPP_{d,total,i} = AEPP_{d,i} * NB_{d,i} * NT \tag{8}$$

$AEPP_{d,i}$ is the annual wind energy production potential of a single turbine in domain d, in wind group i and it is calculated through equation (9).

$$AEPP_{d,i} = \sum_{j=1}^{M} \frac{P_j + P_{j+1}}{2} * 8760 * \left[e^{-\left(\frac{U_j}{A_i}\right)^{k_i}} - e^{-\left(\frac{U_{j+1}}{A_i}\right)^{k_i}} \right] \tag{9}$$

M is the total number of wind speed bins, P_j denotes the turbine power output at the lower bound wind speed of wind speed bin j and P_{j+1} denotes the power output at the upper bound of wind speed bin j. The power output of a specific wind speed is derived from the power curve of the turbine. U_j is the corresponding lower bound wind speed of wind speed bin j, U_{j+1} is the upper bound wind speed of wind speed bin j. The average power output of a single turbine

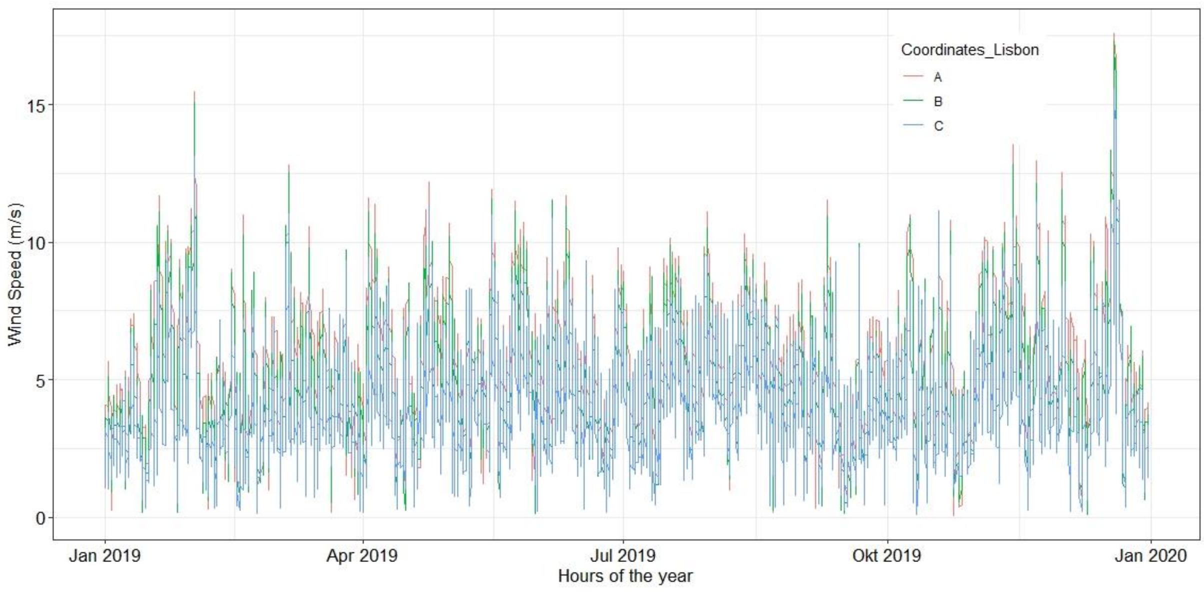
[5] The power coefficient is the ratio between electric power produced by a turbine and the total wind power that meets the blades. It is commonly used to measure the efficiency of a turbine.

$\left(\sum_{j=1}^{M}\frac{P_j+P_{j+1}}{2}\right)$ is multiplied with the average number of hours per year (8760) and with the probability of obtaining wind speeds belonging to wind speed bin j, given the shape and scale parameters A_i and k_i and the respective wind group i. The probability is derived from the Weibull cumulative distribution function, displayed in equation (2).

4. Empirical analysis

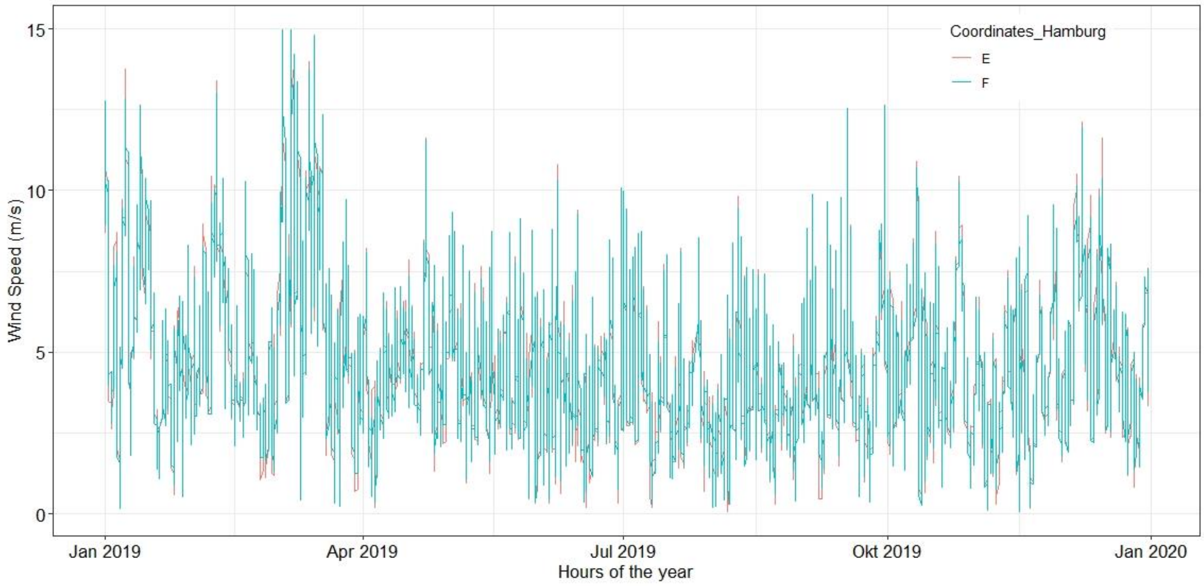
This analysis takes into consideration the cities of Hamburg, Lisbon and Boston, Massachusetts which are expected to have considerable wind-farming potential, especially due to their respective locations close to the coast. Figure 5 displays hourly wind speeds in 2019 from reanalysis data (MERRA2) at the different raster-corner coordinates that are relevant in this analysis. For the specific location of the coordinates, see Figure 8. It can be observed, that among all domains wind speeds in winter months are considerably higher than in summer months. This is quite interesting if an adequate mix of solar and wind power is to be exploited during the year as solar power generation is typically rather modest in the winter period.

Figure 5: Hourly wind speeds at 10 m height in 2019 for the three MERRA2-coordinates relevant for the considered buildings in Lisbon.



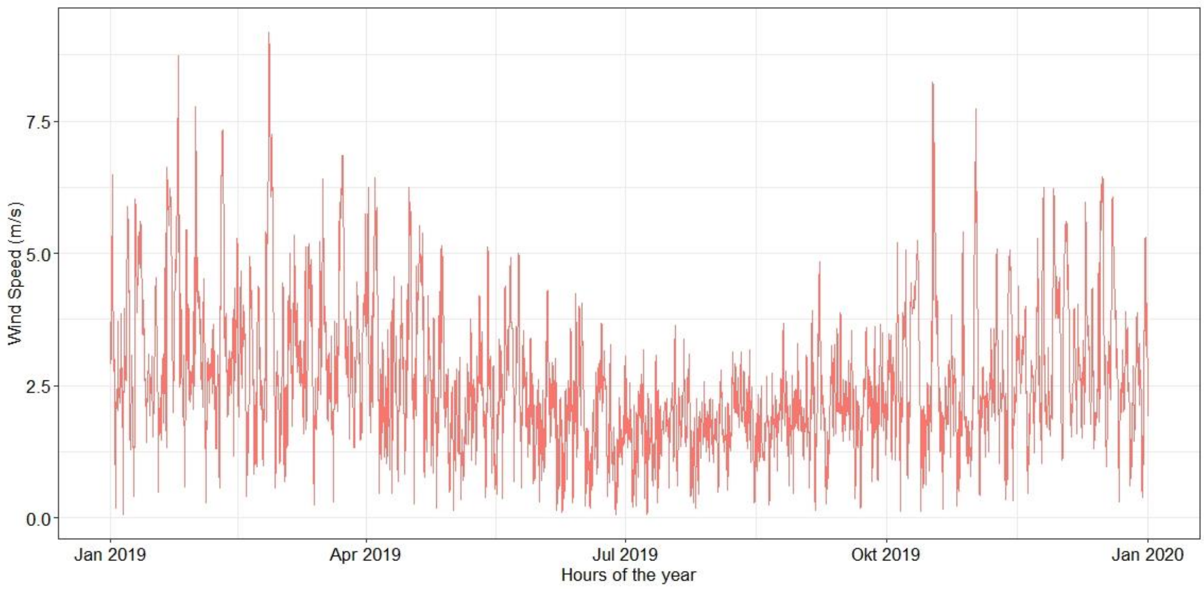
Source: Own representation based on MERRA2 data (NASA, 2019)

Figure 6: Hourly wind speeds at 10 m height in 2019 for the two MERRA2-coordinates relevant for the considered buildings in Hamburg.



Source: Own representation based on MERRA2 data (NASA, 2019)

Figure 7: Hourly wind speeds at 10 m height in 2019 for the MERRA2-coordinate relevant for the considered buildings in Boston, Massachusetts.



Source: Own representation based on MERRA2 data (NASA, 2019)

4.1 Building data

The building data for this analysis is obtained from www.emporis.com, a global provider of building information. Their openly available online database comprises different types of buildings for over 18,000 cities worldwide, amongst other attributes including the building height, building type (e.g., “high-rise building”, “low-rise building”, “skyscraper”), status (e.g., “existing”, “under construction”, “demolished”) and, in most cases, also addresses (Emporis, 2020).

This analysis only includes building types have a high chance of being good locations for wind turbines, i.e., are sufficiently high and are likely to provide a large-enough roof-surface. The considered building types as defined by Emporis (2020), are listed in Table 1.

Table 1: Definition of building types used in the analysis.

Building type	Definition
Skyscraper	A multi-story building at least 100 meters tall.
High-rise building	A multi-story structure between 35-100 meters tall, or a building of unknown height from 12-39 floors.
Low-rise building	An enclosed structure below 35 meters which is divided into regular floor levels.
Stadium	An indoor or outdoor arena for sporting events and spectators.
Hall	An enclosed structure dominated by very large undivided spaces.

Source: Own representation based on information by EMPORIS (2020)

Buildings below 20 m are excluded from the analysis, as they are more likely to be covered by surrounding buildings. Additionally, only buildings that are already existing or are being under construction enter the analysis (buildings with status “planned”, “demolished” or “unbuilt” are excluded). Table 2 displays the number of buildings of each building type that enter the analysis for each domain.

Table 2: Number of buildings per building type in each city

Domain	Skyscraper	High-rise	Low-rise	Stadium	Hall	Sum
Hamburg	3	254	451	2	0	**710**
Lisbon	3	224	36	0	1	**264**
Boston	56	257	357	1	0	**671**

Source: Own representation of data based on EMPORIS data (Emporis, 2020).

Each building must now be assigned to height groups according to the minimum and maximum building height across all domains. For this analysis, height groups are separated in 10 m steps, with height group 20 deviating as it includes all buildings that are larger or equal 210 m (the largest building across all domains is 241 m high). The reference height is chosen based on the average between the lower and upper bound of the height group range. Table 3 displays the chosen height groups and the corresponding number of buildings in each subdomain. Note, that for the height groups, the lower limit is inclusive and the outer limit exclusive.

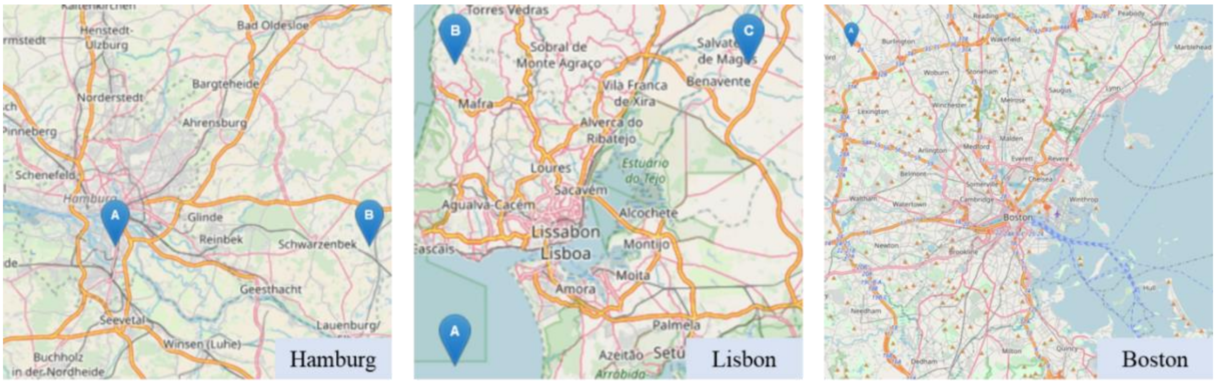
Table 3: Height groups, reference heights and respective number of buildings per city

Height Group			Domain		
	Range	**H_r**	**Hamburg**	**Lisbon**	**Boston**
1	20-30	25	348	9	167
2	30-40	35	94	30	157
3	40-50	45	113	70	127
4	50-60	55	104	106	49
5	60-70	65	25	23	47
6	70-80	75	13	17	24
7	80-90	85	5	4	21
8	90-100	95	5	2	20
9	100-110	105	2	1	8
10	110-120	115	1	2	9
11	120-130	125	-	-	10
12	130-140	135	-	-	4
13	140-150	145	-	-	3
14	150-160	155	-	-	10
15	160-170	165	-	-	5
16	170-180	175	-	-	-
17	180-190	185	-	-	5
18	190-200	195	-	-	-
19	200-210	205	-	-	1
20	≥210	215	-	-	4
Sum			**710**	**264**	**671**

Source: Own calculations

Following the assignment to height groups, the next stage is to prepare the building dataset for the merging with the wind data. In order to assign each building to its closest MERRA2 grid corner, coordinates for each relevant building were added manually through a Google Maps search. The assignment of the closest grid corner is done through the minimization of the distance between building and available grid corners, such that the best available wind speed observation is used for the further analysis. Figure 8 displays the closest MERRA2 grid coordinates for the relevant buildings in each domain.

Figure 8: Relevant MERRA2 coordinates for the sample domains



Source: Own representation through Geoplaner (2020) and OpenStreetMap (2020).

The building dataset now comprises the building location (through coordinates) and the building height. In the next step, wind data must be prepared for the merge with the building data.

4.2 Wind data

The Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA2) dataset from NASA comprises reanalysis data for different weather/climate variables from 1980 to the present day. The MERRA2 data is well suited for long-term analysis and comparison as it combines reliable and complete weather observations in a standardized manner on a global scale, mitigating observation gaps of meteorological stations and long-distance interpolation.

In this analysis, we use a time-averaged, two-dimensional data collection with hourly observations (short name: M2T1NXSLV) (GES DISC, 2020) over 30 years (1990 to 2019)[6] (Global Modeling And Assimilation Office and Pawson, 2015) . The dataset is available in a grid with a spatial resolution of 0.5 ° x 0.625 °, which roughly corresponds to 55 km x 41 km in Hamburg, 55 km x 54 km in Lisbon, and to 56 km x 31 km in Boston, Massachusetts.

Wind data is available at 2 m, 10 m and 50 m above ground and consist of eastward (u) and northward (v) wind vectors that allow the calculation of wind speed (ws) and direction. The

[6] In the Hamburg MERRA2 dataset, five files were damaged, corresponding to four days (120 hours) of wind data. These hourly observations could not be included in the analysis. This however should not affect the general results.

calculation of wind speed is straightforward and performed using the Pythagorean Theorem as displayed in equation (10).

$$ws = \sqrt{u^2 + v^2} \tag{10}$$

The u-vector runs parallel to the x-axis; a positive u is wind from the west, a negative u is wind from the east. The v-vector runs parallel to the y-axis; a positive v is wind from the south, a negative v is wind from the north (George Mason University, 2014).

Vertical extrapolation of wind data

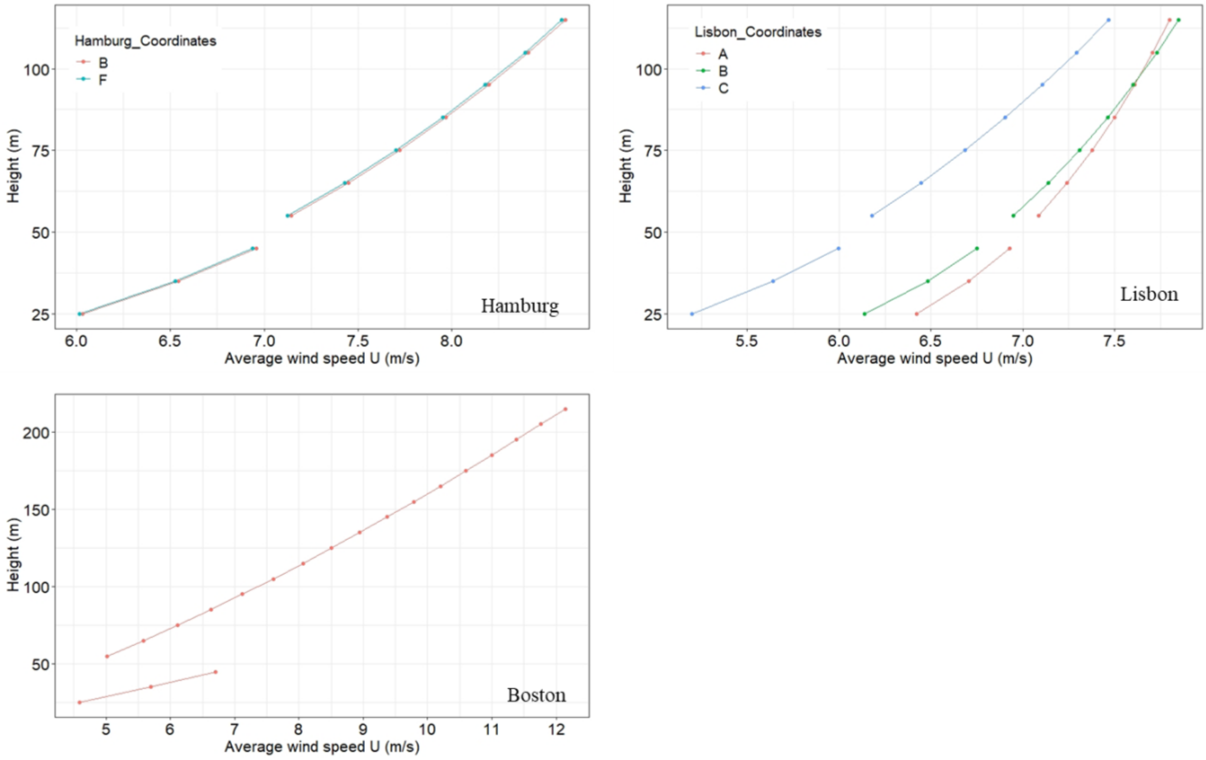
The wind speed data at each relevant raster corner of the MERRA2 dataset is extrapolated to the reference height of the height groups (see Table 3) for each domain. Vertical extrapolation is performed through the application of the power law (equation (4)), with an individual WSC coefficient (equation (5)) being calculated for each hourly wind speed datapoint. For height groups 1, 2 and 3 ($H_r = 25m/\ 35m/45m$), 10 m is used as a baseline height H_b. For the remaining height groups 4-20, 50 m is defined as the baseline height H_b. The corresponding baseline height was chosen based on the closest MERRA2 wind measurement that is smaller than the reference height (note that MERRA2 wind data is available at 2 m, 10 m and 50 m). The WSC α is calculated for each hour and coordinate of the wind dataset for each domain, according to equation (5). For equation (5) wind speeds at two different heights are required, here the available MERRA2 wind data at 2 m and 50 m were used to derive the hourly wind shear coefficients. In some cases, the wind shear coefficient is negative which seems counterintuitive for the extrapolation of wind speeds. Extrapolated wind speeds that are derived with a negative wind shear coefficient are smaller than the wind speed at the wind speed at reference height. Although counterintuitive, negative wind shear coefficients are determined by the available data and must therefore be included.

Weibull groups

For each domain there is now a table with hourly wind speeds at each relevant MERRA2 raster corner and each reference height available. For Lisbon, there are three relevant raster corners and 10 height groups, which results in 30 Weibull groups. For Hamburg, there are two relevant raster corner and also 10 height groups, such that 20 Weibull groups are derived. In Boston, only one coordinate from the MERRA2 raster is relevant for the Boston building-dataset. Boston has 20 height groups, such that 20 Weibull groups are derived.

Figure 9 shows the (undisturbed) mean wind speeds for each reference height and each MERRA2 raster corner for three domains. Please note, that the interrupted lines for each coordinate are due to the fact that the baseline height, which is necessary for the extrapolation of wind speeds (see equation (4)), must be smaller than the reference height. Therefore, for height groups 1-3, wind data at 10 m height is used as a baseline height, while for the remaining height groups, wind data at 50 m height is applied as a baseline height.

Figure 9: Undisturbed average wind speeds at reference heights



Source: Own calculations and representation

It is striking that the wind speeds at the MERRA2 raster corner (coordinates) in Hamburg show very similar, almost the same, average wind speeds, as compared to the raster corner average wind speeds in Lisbon. This might primarily be due to the location of the raster corners, as displayed in Figure 8. The coordinates in Hamburg are both located on the mainland without obstacles (such as other cities or mountains) or fallow land (that allows for the undisturbed flow of wind) in between. As compared to Lisbon, where one raster corner lies in the ocean (A), one is very close to the coast (B) and one lies on the mainland (C). In Boston, Massachusetts, there is only one raster corner that is relevant for the buildings in the dataset, therefore there is only one line displaying undisturbed average wind speeds. Due to the change of the extrapolation regime that was explained before, there is a break in the data line at 55 m height. The average wind speed at a reference height of 65 m is smaller than the one at 55 m, however increases steadily with height afterwards.

For each Weibull group, the parameters of the Weibull distribution (shape parameter A and scale parameter k) are derived through appliance of a maximum likelihood estimation. Consequently, each building is assigned a Weibull group, depending on its affiliation to its closest MERRA2 raster corner and its affiliation to a height group.

Wind groups

The shape and scale parameters of the Weibull groups in each domain are rounded in order to reduce the total number of wind groups. For Lisbon and Boston, there is a lot of variation in the scale parameter A, wherefore it is rounded to a full number and the shape parameter k is rounded to one decimal place. Consequently, six wind groups are created for Lisbon and 12 wind groups are created for Boston. Wind speeds in Hamburg do not show as much variation in the scale parameter as compared to the shape parameter. Therefore, both Weibull parameters are rounded to one decimal place, which leads to 10 wind groups for Hamburg.

The wind groups with their Weibull distribution parameters, their mean wind speeds and the number of affiliated buildings is shown in Table 4.

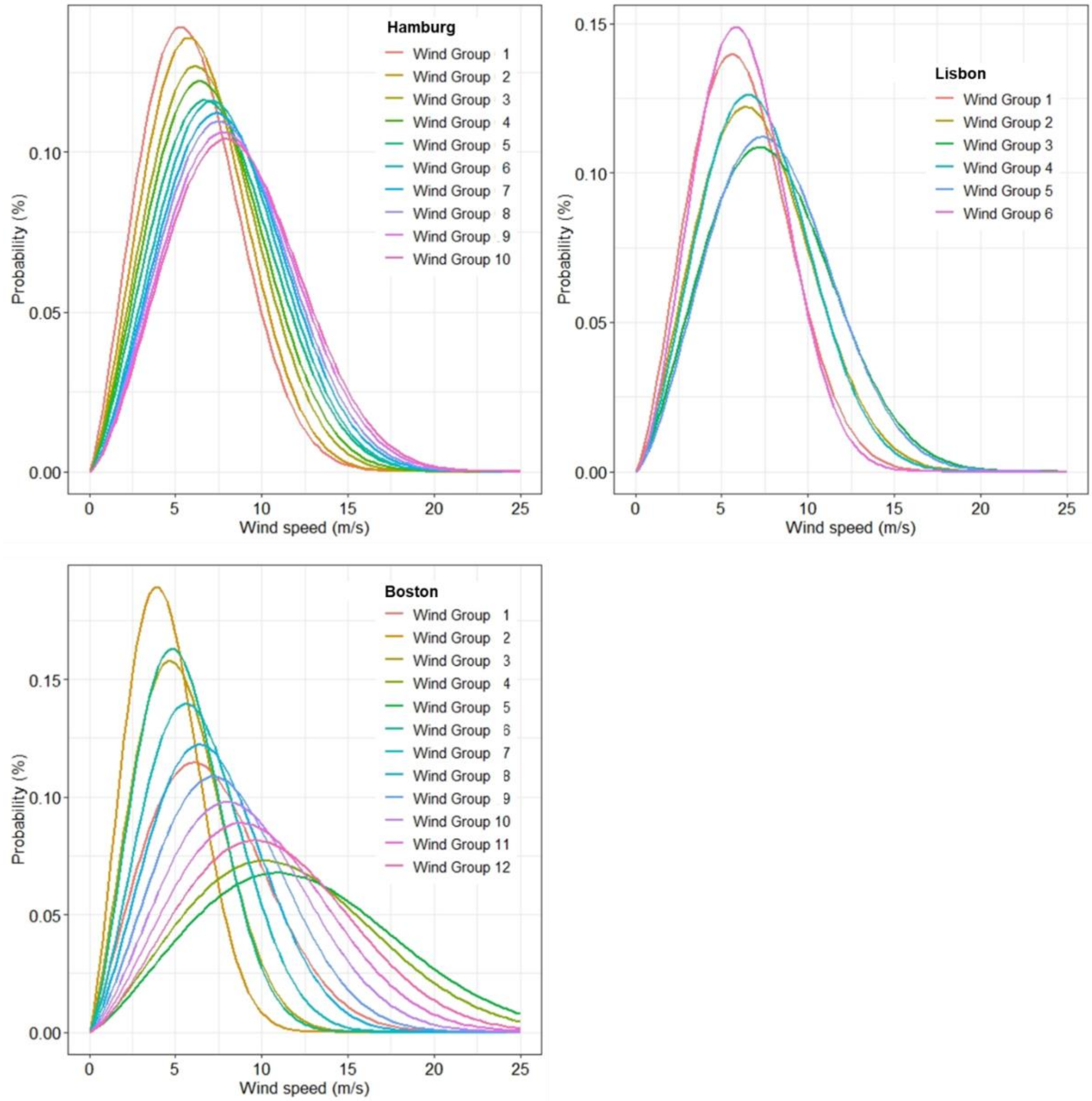
Table 4: Wind Groups with Weibull parameters and affiliated buildings.

	Wind Groups Hamburg			**Wind Groups Lisbon**			**Wind Groups Boston**		
	A	**k**	**Number of buildings**	**A**	**k**	**Number of buildings**	**A**	**k**	**Number of buildings**
1	6.8	2.3	348	7	2.4	13	8	2.2	127
2	7.4	2.3	94	8	2.4	182	5	2.3	167
3	7.8	2.4	113	9	2.4	3	6	2.3	157
4	8	2.4	104	8	2.5	62	13	2.3	1
5	8.4	2.4	25	9	2.5	2	14	2.3	4
6	8.7	2.5	13	7	2.6	2	6	2.4	96
7	9	2.5	5				7	2.4	45
8	9.2	2.5	5				8	2.4	20
9	9.5	2.5	2				9	2.4	17
10	9.7	2.5	1				10	2.4	14
11							11	2.4	18
12							12	2.4	5

Source: Own calculations and representation

The associated Weibull distributions for each wind group in each domain are plotted in Figure 10. In Lisbon and Hamburg, it can be observed that the distributions of the wind groups have similar means and larger shape parameters than the Weibull distributions of the wind groups in Boston, which makes their Weibull distribution sharper. The wind groups in Boston show overall lower shape parameters which vary between 2.2-2.4 than the wind groups in Lisbon and Hamburg, whose shape parameters vary between 2.3-2.6 (see Table 4), indicates a broader distribution of wind speeds.

Figure 10: Weibull distributions for wind groups



Source: Own calculations and representation

After the determination of rounded scale and shape parameters for each wind group, the number of hours depending on the wind speed can be derived. The wind speed range in each domain, as well as the cut-in and cut-off wind velocity of the sample turbine, determines the wind speed bins for which the number of hours are derived from the Weibull cumulative distribution function W(U), as displayed in equation (2). The cut-in wind speed of the chosen turbine is 2.5 m/s and has a survival wind speed of 52.5 m/s. Due to the high survival wind speed, the maximum wind speed among the Weibull groups (46.8 m/s) determines the upper bound of the wind speed bins, namely 48 m/s (see Table 5). 23 wind speed bins are consequently derived.

Table 5: Minimum and maximum wind speeds in the sample domains

	Minimum wind speed among all Weibull groups	**Maximum wind speed among all Weibull groups**
Lisbon	0 m/s	32.04 m/s
Hamburg	0 m/s	31.6 m/s
Boston	0 m/s	46.8 m/s

Source: Own calculations

4.3 Turbine Data

For this analysis, a small 4-bladed VAWT (H-Darrieus rotor) was selected. The manufacturer Aeolos offers three types of VAWT that are all applicable for roof-top installation. Here, the most powerful VAWT, namely Aeolos-V-3kW, is chosen. Basic technical information on the turbine is given in Table 6.

Table 6: Technical data of the sample turbine Aeolos-V-3kW

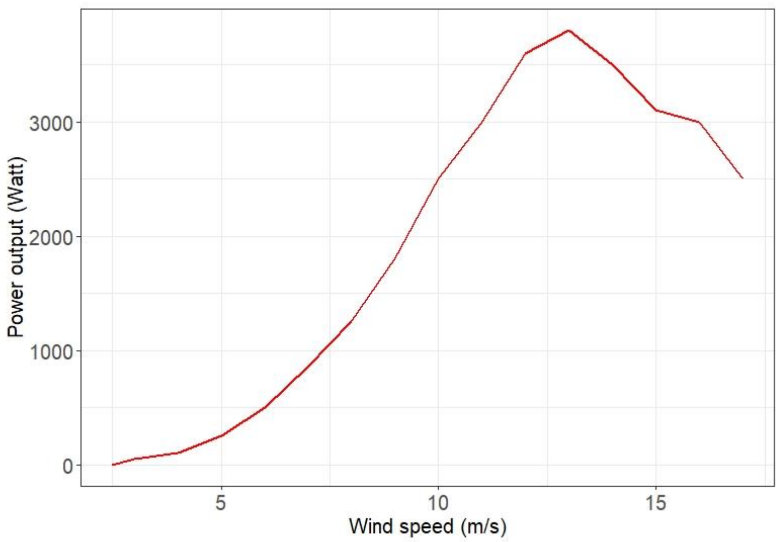
Aeolos-V-3kW turbine	
Manufacturer	Aeolos Wind Energy Ltd.
Rated wind speed	11 m/s
Rated power	3 kW
Maximum power	3.8 kW
Cut-in speed	2.5 m/s
Survival wind speed	52.5 m/s
Rotor height	3.6 m
Rotor diameter	3 m
Total weight	106 kg
Noise level	< 45 dB(A)
Warranty	5 years
Design Lifetime	20 years
Blades RPM limitation	320 RPM

Source: Aeolos product booklet for Aeolos-V-3kW, provided on request from the manufacturer (Aeolos Windenergie GmbH, 2020)

The low cut-in wind speed of 2.5 m/s allows for an almost continuous wind energy production even at low wind speeds. Aeolos-V-3kW also deals well with higher wind speeds and survives velocities up to 52.5 m/s. The maximum power output of 3.8 kW is generated at a wind speed of 13 m/s. Compared to the wind conditions in the sample domains, displayed in Table 5, the turbine should perform well and safely. Additional security, especially at high wind speeds, is provided by a limitation to the blade rotation per minute and a mechanical break that can be activated automatically or manually.

The noise level of the Aeolos-V-3kW turbine is very low (< 45 dB(A)); i.e., less noisy than a common household refrigerator, which emits approximately 55 dB(A) (EHS Yale, 2020). The manufacturer provides a power curve in the product brochure, which determines the power output of the turbine for wind speeds up to 16 m/s. Unfortunately, no further information on the performance of the turbine for higher wind speeds could be obtained. Therefore, a constant power output of 2.500 W is assumed for wind speeds from 17 m/s to 35 m/s. Higher wind speeds are not part of the datasets of the sample domains. From the available values, the power curve was extended to the whole range (2.5 m/s-35 m/s) by curve fitting. The power curve can then be stated as displayed in Figure 11. As the power output is assumed to stay constant after reaching an input wind speed of 17 m/s, in the graphical representation, the power curve is only shown until this limit.

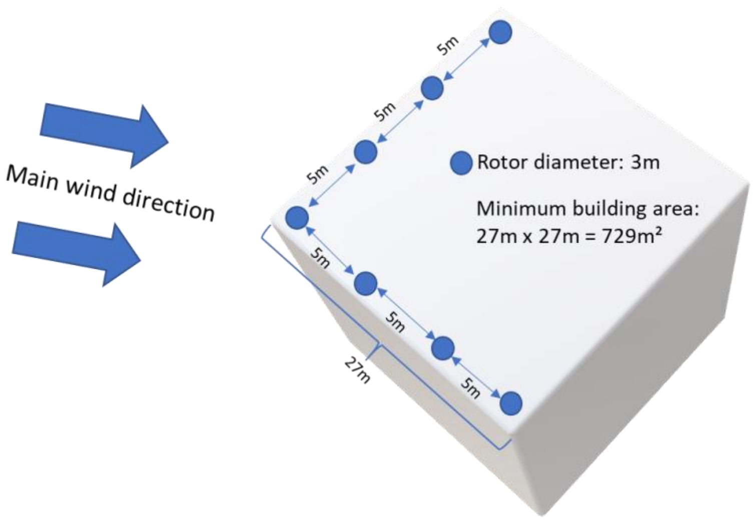
Figure 11: Power curve of the sample turbine Aeolos-V-3kW



Source: Own calculations based on information in the product booklet for Aeolos-V-3kW (Aeolos Windenergie GmbH, 2020)

Rezaeiha et al. (2020) assume the arrangement of 12 counter-rotating VAWT per building roof, while considering the mutual performance impact (wake effect) of the turbines through the constant coefficient $C_W = 0.88$. The coefficient was derived for a dual array of turbines with co- and counter-rotational directions and relative spacings between 1.25 to 10 turbine diameters. The rotor diameter of the Aeolos-V-3kW sample turbine is 3 m. This is three times the diameter of the sample turbine used by Rezaeiha et al. (2020), wherefore this analysis assumes a lower average number of turbines per roof and is performed under three scenarios (each with a varying number of turbines per roof). Scenario 1 assumes three installed turbines per building (counter-rotationally installed on each building corner), Scenario 2 assumes five turbines and Scenario 3 seven turbines per building. If we assume a rectangular building shape and a security spacing of 5 m between the turbines, the turbine installation could look like represented in Figure 12.

Figure 12: Exemplary building with seven installed turbines.



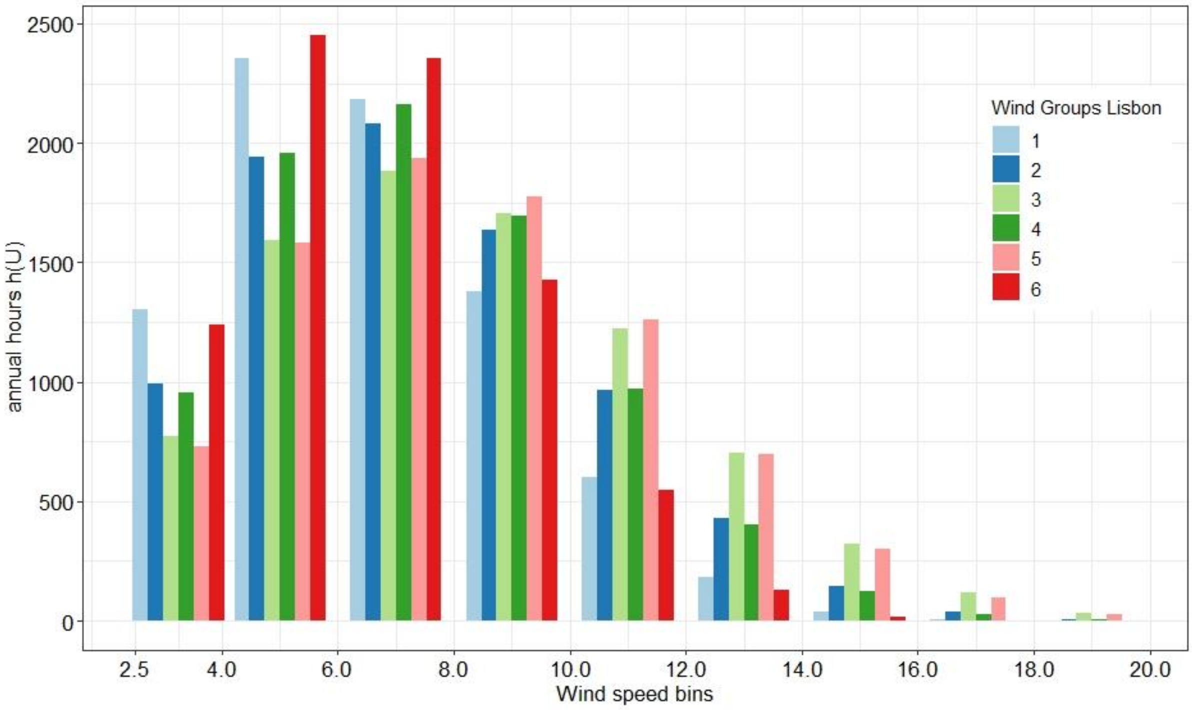
Source: Own representation.

4.4 Wind energy potential in each domain

The subsequent tables show the results of the wind energy production potential analysis for the different domains, following equations (7) - (9). The annual energy production potential (AEPP) of a single turbine per wind group and wind bin (with the mean wind speed per wind group U (m/s) derived with equation (3)) is given in Appendix-Tables 1-3 for each domain. Note, that only wind speed bins with production values larger than zero (rounded to zero decimal points) are displayed. Appendix-Tables 1-3 display how much AEPP a single turbine has in the city of Hamburg, Lisbon or Boston respectively, assuming the probability distribution of wind speeds for each wind group. Even though higher wind speeds produce a higher energy output, the production potential for higher speeds (e.g., wind speed bin 30-32) is rather low or even close to zero for many wind groups. This is due to the fact that very high wind speeds are rare throughout an average year and therefore have a lower occurrence probability. For a better illustration, see also Figure 10, where the Weibull distributions for Hamburg, Lisbon and Boston are presented. In Hamburg, the highest aggregate AEPP is generated by wind group 10, followed by wind groups 9. In Lisbon, the sum of the AEPP for each wind group indicates that wind group 5 has the highest energy production potential, closely followed by wind group 3. For Boston, wind groups 5 has the highest energy production potential across all wind bins, followed by wind group 4.

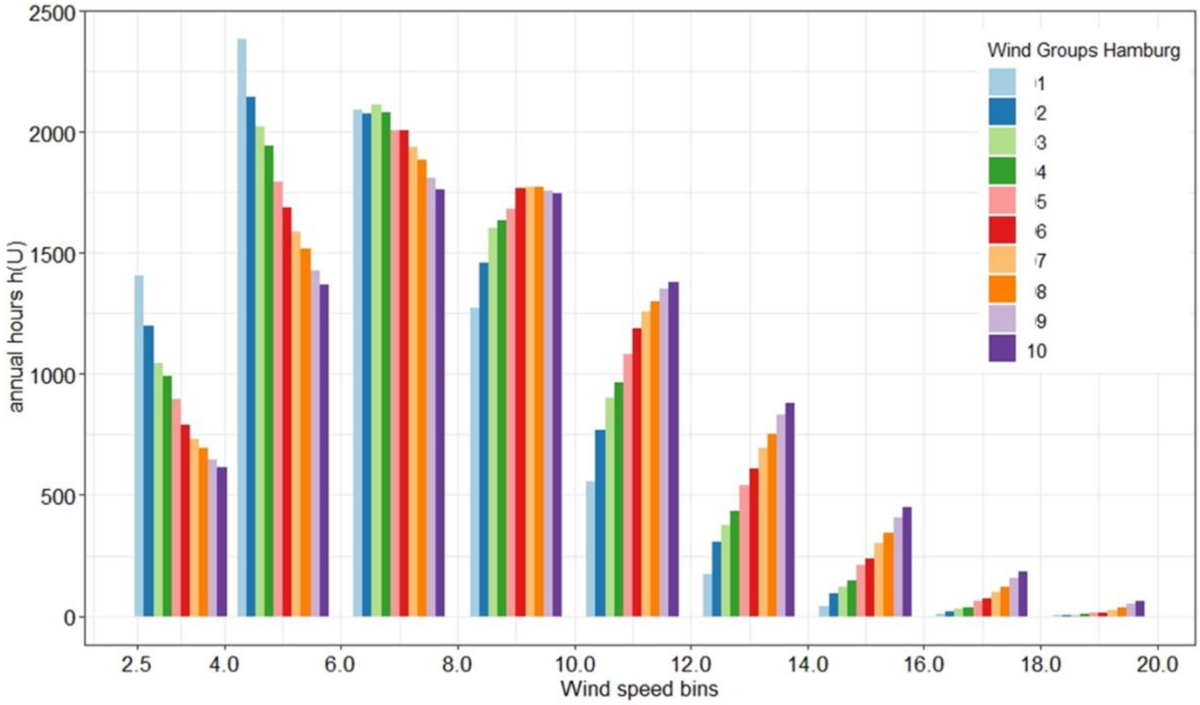
The number of hours for each wind speed bin during one year are shown in the subsequent Figures 13-15. Since wind speeds over 20 m/s are very rare, wind speed bins in these figures are cut at this benchmark for the sake of a clear graphical representation. Note, that for the calculation of the AEPP, all wind speed bins are included. Finally, Tables 7-9 show the AEPP for each domain. In Lisbon, 7,305 MWh can annually be produced through the installation of three turbines on 264 buildings. The production can be increased to 12,176 or 17,046 MWh if five or respectively seven turbines were installed on each building. In Hamburg, the AEPP amounts to 16,664 MWh, produced by three turbines on the roofs of 710 buildings. Five turbines on each building produce to 27,773 MWh and seven turbines per building 38,883 MWh. The AEPP in Boson, Massachusetts amounts to 12,502 MWh produced by three turbines on 671 roofs and can be increased to 20,837 MWh if five turbines are installed on each building and to 29,171 MWh if seven turbines were installed.

Figure 13: Lisbon - Annual number of hours for each wind speed bin and wind group. Each wind group having unique A and k.



Source: Own calculations and representation

Figure 14: Hamburg - Annual number of hours for each wind speed bin and wind group. Each wind group having unique A and k



Source: Own calculations and representation

Figure 15: Boston, Massachusetts - Annual number of hours for each wind speed bin and wind group. Each wind group having unique A and k

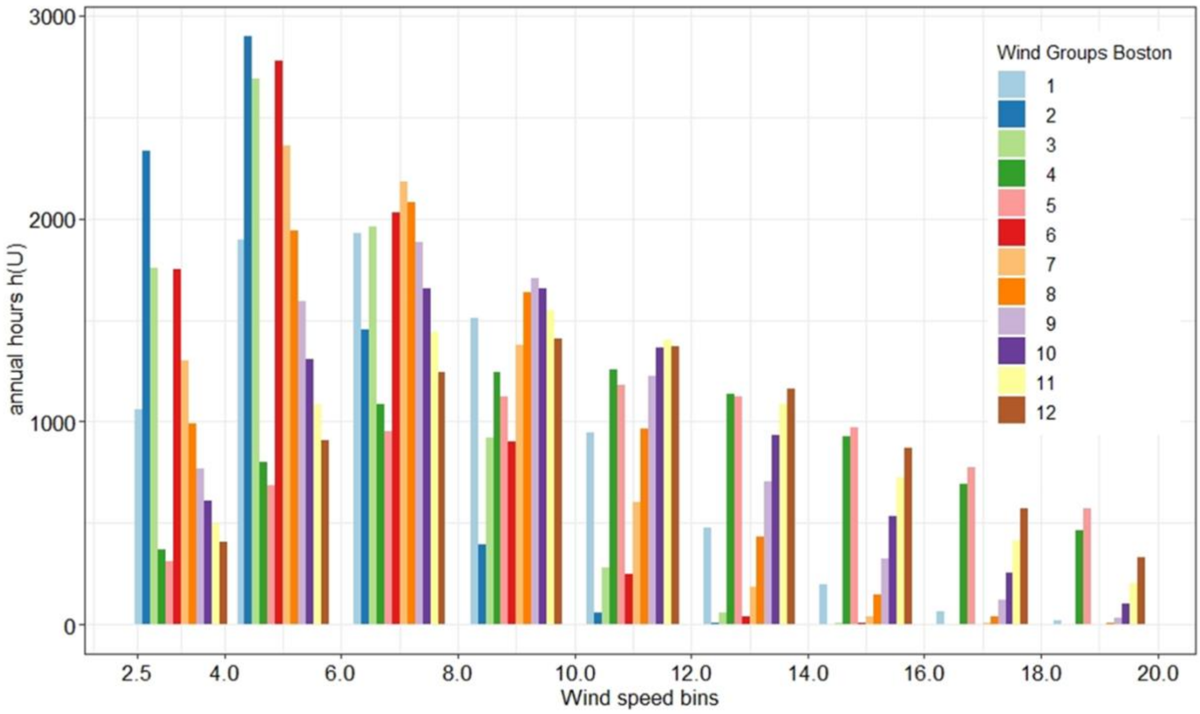


Table 7: Total AEPP in Lisbon (three scenarios)

Lisbon		Wind Group					
		1	2	3	4	5	6
$AEPP_{Lisbon,i}$ (kWh)		7,898	10,591	13,087	10,578	13,166	7,739
$NB_{Lisbon,i}$		13	182	3	62	2	2
$AEPP_{Lisbon,total,i}$ (MWh)		411	7,711	157	2,623	105	62
C_W		0.88	0.88	0.88	0.88	0.88	0.88
Total buildings		264					
Scenario 1 (three turbines)	Total turbines	792					
	$AEPP_{Lisbon,total}$	**7,305 MWh**					
Scenario 1 (five turbines)	Total turbines	1,320					
	$AEPP_{Lisbon,total}$	**12,176 MWh**					
Scenario 1 (seven turbines)	Total turbines	1,848					
	$AEPP_{Lisbon,total}$	**17,046 MWh**					

Source: Own calculations

Table 8: Total AEPP in Hamburg (three scenarios)

Hamburg		Wind Group									
		1	2	3	4	5	6	7	8	9	10
$AEPP_{Hamburg,i}$ (kWh)		7,454	9,043	10,061	10,591	11,626	12,422	13,166	13,644	14,330	14,767
$NB_{Hamburg,i}$		348	94	113	104	25	13	5	5	2	1
$AEPP_{Hamburg,total,i}$ (MWh)		10,377	3,400	4,548	4,406	1,163	646	263	273	115	59
C_W		0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Total buildings		710									
Scenario 1 (three turbines)	Total turbines	2,130									
	$AEPP_{Hamburg,total}$	**16,664 MWh**									
Scenario 2 (five turbines)	Total turbines	3,550									
	$AEPP_{Hamburg,total}$	**27,773 MWh**									
Scenario 2 (five turbines)	Total turbines	4,970									
	$AEPP_{Hamburg,total}$	**38,883 MWh**									

Source: Own calculations

Table 9: Total AEPP in Boston, Massachusetts (three scenarios)

Boston	**Wind Group**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$\boldsymbol{AEPP_{Boston,i}}$ (kWh)	10,607	3,198	5,408	18,968	19,717	5,295	7,898	10,591	13,087	15,220	16,940	18,277
$\boldsymbol{NB_{Bostoni}}$	127	167	157	1	4	96	45	20	17	14	18	5
$\boldsymbol{AEPP_{Boston,\ total,i}}$ (MWh)	5,388	2,137	3,396	76	315	2,033	1,422	847	890	852	1,220	366
$\boldsymbol{C_W}$	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Total buildings	671											

Scenario 1 (three turbines)	Total turbines	2,013
	$\boldsymbol{AEPP_{Boston,total}}$	**12,502 MWh**
Scenario 2 (five turbines)	Total turbines	3,355
	$\boldsymbol{AEPP_{Boston,total}}$	**20,837 MWh**
Scenario 3 (seven turbines)	Total turbines	4,697
	$\boldsymbol{AEPP_{Boston,total}}$	**29,171 MWh**

5. Discussion

The total AEPP of seven turbines in Lisbon (17,046 MWh) corresponds to the average annual electricity consumption of approximately 13,275 residents or to 0.45 % of the approximate total annual electricity consumption in Lisbon[7] (Eurostat, 2020a). This seems to be a rather modest number; however, it should be noted that that only 264 buildings were included in the preliminary production potential simulation for Lisbon. Lisbon is a very flat city, with few high-rise buildings or skyscrapers, therefore its production potential might be considerably higher if the cut-of benchmark of 20 m were adjusted downwards for the Lisbon building dataset.. The total AEPP of seven turbines in Hamburg is approximately 193 % higher than in Lisbon and amounts to 38,883 MWh. On average, 1.40 % of the annual residential electricity consumption in Hamburg could be replaced through the turbines, which relates to the annual electricity consumption of 25,110 residents in Hamburg[7]. The difference in production potential between Hamburg and Lisbon arises mainly due to the fact that Hamburg has considerably more buildings that are at least 20 m in height and therefore enter the analysis. The Hamburg building dataset comprises 2.6 times more buildings than the Lisbon dataset. There are around 40 more buildings in the Boston building dataset than in the Hamburg dataset. Also, Boston has considerably more very high buildings than Hamburg (see Table 3). Still the AEPP of Hamburg is on average (over all scenarios) 33 % higher than the AEPP of Boston. This might foremostly be due to the technical performance of the chosen exemplary turbine. The turbines energy output shows a decreasing marginal energy yield. The power curve is assumed to reach its maximum energy production 3000 Watt at a wind speed of 16 m/s and to decrease to a production of 2500 Watt at a wind speed of 18 m/s onwards (see Figure 11). In order to maximize the energy production in Boston by exploiting the high wind speeds on the many skyscrapers and high-rise buildings, a different turbine should be used that is more applicable for high wind speeds (such as HAWT). The total AEPP of seven turbines in Boston amounts to 29,171 MWh. This covers the average annual electricity consumption of approximately 6,400 residents or 0.92 % of the population (IEA, 2020). Boston has considerably less residents than Hamburg[8] but the per-capita annual electricity consumption of an average person in the USA is however almost 3 times higher than the average annual electricity consumption of a German person. Thus, the AEPP in Boston covers only 0.92 % of the residential electricity consumption, while the AEPP in Hamburg covers almost 1.40 % of the residential electricity consumption. Certainly, to this also contributes the overall higher AEPP in Hamburg.

The representation of the annual number of hours for each wind speed bin and wind group in Figures 13-15 gives insights into the production potential of the different domains, technical requirements of turbines and possible combination with other renewable energy generators (such as solar energy) by displaying the most frequent wind speeds throughout the year. The frequency of the different wind speeds in each wind group should be considered when choosing the optimal turbine for specific locations throughout a city.

This analysis gives a good preliminary insight into the general wind energy production potential of two European and one US-American coastal cities. It especially adds a new feature to the approach from Rezaeiha et al. (2020) by introducing globally and openly available reanalysis

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[7] Consumption data as of 2018 (EUROSTAT, 2020).

[8] As of 2018, Hamburg had 1,793,000 residents, Boston had 694,583 residents.

data from NASA to the framework and drawing a cross-country comparison. The framework can further be extended to make the analysis more detailed. However, increased precision of the results might decrease simplicity and applicability to global comparisons. Two improvements, however, might increase accuracy of the analysis without introducing to much complexity:

Firstly, the building dataset might be increased by including lower buildings, especially for flat cities, like Lisbon. Secondly, the AEPP can be increased by using a more efficient turbine. The choice of a sample turbine for this analysis was very much limited to the willingness of manufacturers to provide a power curve to the authors. Future co-operation with a specific manufacturer of SWTs that are applicable for roof-top installation might avoid this problem (via provision of a more detailed power curve, more technical information and real-world insights). Such a co-operation might even provide access to energy production data from that specific turbine, which could be used to examine the robustness of the framework.

6. Concluding remarks and policy perspectives

Urban wind farming could be an important and geographically focused part of the broader expansion of renewable energy. However, urban wind electricity generation could generate some problems if one considers roof-mounted wind turbines (other forms of urban wind farming are, however, also conceivable):

- There might be emissions from noise and flickering (i.e. the shadows from moving blades of wind energy turbines) plus sun reflection could affect neighboring buildings.

- Technical standardization of urban wind turbines seems to be rather modest, even across the EU (Cace et al., 2007)

Nonetheless, there are also crucial advantages which partly go beyond the particular investment case for urban wind farming. The main advantages as emphasized by Cace et al. (2007) can be summarized here (with an additional argument in the end):

- *"CO2 savings;*

- *Green electricity generation;*

- *Meeting the requirements regarding energy saving and renewable energy appliances…;*

- *Preventing energy transport losses from large power plants to the consumer;*

- *Stimulate change of attitude: individual energy producers are typically more energy efficiency aware;*

- *Saving of fossil fuel resources;*

- *A visible "green" image for marketing purposes and emphasis on socially involved entrepreneurship;*

- *Role model function: a government organization leads by example to encourage businesses;*
- *Savings on energy costs;*
- *Less concerns regarding rising energy prices;*
- *Less dependency on energy utility companies;*
- *Development of export product"*

The rise of CO2 emission certificate prices in Europe and in other countries where the energy sector (and industry – as in the EU) is subject to an Emission Trading System will stimulate substitution in favor of renewable energy; and here, wind energy, including urban wind farming, has a massive medium-term potential.

Technological development of small wind turbines for the urban environment is ongoing, especially regarding the improvement of HAWTs for urban usage.

One should not conclude that only those cities close to the sea will have considerable wind power. The higher the buildings in a city are, the higher should be the wind electricity potential so that some of the very big inland cities with many skyscrapers should have considerable wind farming potential. Here, broader perspectives for transatlantic EU-US co-operation as well as for EU-Japan co-operation should be developed. It is noteworthy that the Japanese region around Tokyo has applied ETS to the real estate sector and that considerable efficiency gains in energy generation and in the use of energy could be achieved (Welfens, 2019). Such gains could be enhanced by specific projects in the field of urban wind farming. One may also emphasize that broad urban investment in solar and wind power systems could help to cut grid investments considerably and this would also mean an indirect reduction of CO2 emissions as less production of grid equipment will be needed.

At the same time, it should be emphasized that government regulation and architectural standards for office buildings, factories, businesses and private homes should formulate adequate quality requirements for both physical real estate as well as the quality of the wind electricity generating equipment. As regards standardization, transatlantic or global standardization schemes – largely organized by industry itself (but with some government oversight) – should be considered. One particular long run issue concerns architectural guidelines and standards in the field of city planning. Architectural aspects matter to the extent that urban planning thus far has not considered systematically the opportunities to create favorable conditions for urban wind-farming through an adequate mix of high-rise and smaller buildings.

As regards the regulation of equipment for urban wind farming in the EU (HAWT, VAWT, as well as other types of wind turbines), it would be useful to have an EU framework regulation so that competition in the EU single market will have strong effects on efficiency gains and innovation dynamics, respectively. Without minimum standardization at the EU level, it will be rather difficult to exploit economies of scale and to make the urban wind farming technology a strong export field of the EU. Many EU countries require an energy building passport for real estate to be sold in the market. At least for company buildings/commercial real estate, should one consider that the relevant information would include a basic calculation for solar and wind equipment for the respective building so that prices in the housing market would adequately reflect wind farming and solar farming opportunities. The joint ownership of houses could also be a crucial field of basic regulation – preferably at the national or regional level – since without regulation, the cost of achieving consensus in a multi-party housing unit might be prohibitively high. These regulatory and policy aspects are likely to be relevant in all OECD countries and in the South of the world economy as well. As soon as a more climate-friendly set of architectural standards and construction requirements in cities consider the potential of urban wind farming, there will be tailwinds for SWTs. Global economies of scale could also be considerable once a major international network of cities with considerable wind farming activities has been created. One should not overlook that part of the SWT benefit for the climate and the user, respectively, is not only linked to wind energy harvesting but to avoiding grid investment. Urban cooperatives for wind farming could also become a new field for cooperative projects. If one could reinforce international political cooperation among cities, then best practice diffusion could benefit. Once a kind of urban wind farming standard has been established, policy makers might want to consider what measures will allow to achieve a quintupling of urban wind farming within a decade. Additional wind energy harvesting could be achieved if certain locations in windy cities would be opened up for more wind farming or combinations of wind farming and solar electricity generation.

Intelligent urban renewable energy policy should include broad common EU standards not just for wind farming but also common standards for passive energy homes; here, Austrian firms are leading in the world (Dachs and Budde, 2020), but it is hardly possible to sell such advanced houses to other EU countries. If the task of achieving climate neutrality is taken seriously in the EU, one should carefully consider the broader issues relevant for achieving climate neutrality via a modernized energy sector and related energy-generating equipment. It will depend on the European Commission and the respective Council presidency's initiative as to what extent innovative approaches in this field and in particular also in urban wind farming will be promoted in the European Union. If the EU would be a leader in urban wind farming, the European Commission should consider making this an element of its international climate protection policy.

In many countries the critical mix – beyond hydro power – will be a mix of solar energy and wind energy. As regards urban power generation, there could be a mix of wind farming and solar power where local wind and solar conditions will critically affect the preferred mix. Government promotion of certain forms of renewable energy could also play a particular role. As regards urban wind farming, government regulation – both national, regional and local regulation – will affect wind farming.

Urban wind farming has considerable long-term potential to contribute towards achieving climate neutrality in many cities of the world economy. There could be a noticeable quantitative electricity supply effect as well as an improvement of energy security via more local electricity production so that urban wind farming can contribute to the resilience of the overall energy system. Installing SWTs on roofs requires to renounce the option of a pyramid-like top of skyscrapers, but such requirement does not stand for a crucial additional cost of construction. Our analysis with a focus only on a rather limited number of houses and roofs, respectively, of two major cities could easily be extended to a larger number of cities worldwide. It would be quite useful to create an international network of wind farming cities in the global economy.

Finally, new projects of urban wind farming could become a crucial field of World Bank activities as well as attract financing from the Asian Development Bank, the European Bank for Reconstruction and Development (EBRD), the Inter-American Bank and other regional development banks. The topic of urban wind farming should thus be included on the agenda of the G20 meetings of environmental ministers in the future so that investors in this technology can anticipate a broader adequate international framework and global market expansion in the future. Urban wind farming has a considerable long-term potential in many cities of the world economy to contribute to achieving climate neutrality. There could be a noticeable quantitative electricity supply effect as well as an improvement of energy security via more local electricity production so that urban wind farming can contribute to the resilience of the overall energy system. Installing SWTs on roofs requires to renounce the option of constructing pyramid-like tops for skyscrapers, but such a requirement does not stand for a critical cost of construction. Our analysis, with a focus only on a rather limited number of houses and roofs, respectively, of two major cities, could easily be extended to a larger number of cities worldwide

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Appendix

Appendix Table 1: AEPP (kWh) of a single turbine at different wind speed bins, for each wind group - Hamburg

Hamburg	Wind Groups									
Wind speed bins (m/s)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
2.5-4	70	60	52	50	45	40	37	35	32	31
4-6	715	644	606	583	538	507	476	456	428	411
6-8	1,829	1,817	1,851	1,823	1,758	1,757	1,693	1,650	1,584	1,540
8-10	2,391	2,739	3,002	3,067	3,155	3,317	3,328	3,322	3,298	3,273
10-12	1,692	2,342	2,744	2,945	3,307	3,621	3,842	3,968	4,126	4,211
12-14	614	1,080	1,338	1,531	1,925	2,165	2,471	2,668	2,948	3,122
14-16	125	295	381	472	683	776	971	1,109	1,322	1,466
16-18	17	56	74	101	173	194	272	332	435	510
18-20	2	9	11	17	36	39	63	83	121	152
20-22	0	1	1	2	6	6	12	17	29	39
22-24	0	0	0	0	1	1	2	3	5	8
24-26	0	0	0	0	0	0	0	0	1	1
$\boldsymbol{AEPP_{Hamburg,i}}$	**7,454**	**9,043**	**10,061**	**10,591**	**11,626**	**12,422**	**13,166**	**13,644**	**14,330**	**14,767**
A	6.8	7.4	7.8	8.0	8.4	8.7	9.0	9.2	9.5	9.7
k	2.3	2.3	2.4	2.4	2.4	2.5	2.5	2.5	2.5	2.5
U (m/s)	6.0	6.6	6.9	7.1	7.4	7.7	8.0	8.2	8.4	8.61

Source: Own calculations

Appendix Table 2: AEPP (kWh) of a single turbine at different wind speed bins, for each wind group - Lisbon

Lisbon	Wind Groups					
Wind speed bins (m/s)	**1**	**2**	**3**	**4**	**5**	**6**
2.5-4	65	50	39	48	37	62
4-6	707	583	477	588	476	736
6-8	1,909	1,823	1,646	1,889	1,693	2,061
8-10	2,581	3,067	3,198	3,179	3,328	2,678
10-12	1,841	2,945	3,736	2,959	3,842	1,673
12-14	653	1,531	2,499	1,436	2,471	464
14-16	125	472	1,053	396	971	61
16-18	15	101	328	72	272	4
18-20	1	17	87	10	63	0
20-22	0	2	20	1	12	0
22-24	0	0	4	0	2	0
24-26	0	0	1	0	0	0
$AEPP_{Lisbon,i}$	**7,898**	**10,591**	**13,087**	**10,578**	**13,166**	**7,739**
A	7	8	9	8	9	7
k	2.4	2.4	2.4	2.5	2.5	2.6
U (m/s)	6.2	7.1	8.0	7.1	8.0	6.2

Source: Own calculations

Appendix Table 3:AEPP (kWh) of a single turbine at different wind speed bins, for each wind group - Boston, Massachusetts

Boston	Wind Groups											
Wind speed bins (m/s)	1	2	3	4	5	6	7	8	9	10	11	12
2.5-4	53	117	88	18	16	87	65	50	39	31	25	20
4-6	569	870	806	239	206	834	707	583	477	393	325	272
6-8	1,687	1,273	1,716	949	831	1,777	1,909	1,823	1,646	1,447	1,258	1,089
8-10	2,837	742	1,720	2,334	2,106	1,691	2,581	3,067	3,198	3,105	2,897	2,644
10-12	2,886	179	855	3,834	3,598	749	1,841	2,945	3,736	4,152	4,267	4,180
12-14	1,698	17	198	4,035	3,979	144	653	1,531	2,499	3,305	3,845	4,129
14-16	639	1	23	3,019	3,163	13	125	472	1,053	1,728	2,345	2,820
16-18	181	0	2	1,895	2,134	1	15	101	328	697	1,139	1,569
18-20	45	0	0	1,164	1,424	0	1	17	87	252	511	828
20-22	10	0	0	716	965	0	0	2	20	83	217	423
22-24	2	0	0	401	603	0	0	0	4	23	79	190
24-26	0	0	0	205	348	0	0	0	1	5	25	75
26-28	0	0	0	95	185	0	0	0	0	1	6	26
28-30	0	0	0	40	91	0	0	0	0	0	1	8
30-32	0	0	0	16	41	0	0	0	0	0	0	2
32-34	0	0	0	5	17	0	0	0	0	0	0	0
34-36	0	0	0	2	7	0	0	0	0	0	0	0
36-38	0	0	0	0	2	0	0	0	0	0	0	0
38-40	0	0	0	0	1	0	0	0	0	0	0	0
$AEPP_{Boston,i}$	**10,607**	**3,198**	**5,408**	**18,968**	**19,717**	**5,295**	**7,898**	**10,591**	**13,087**	**15,220**	**16,940**	**18,277**
A	8	5	6	13	14	6	7	8	9	10	11	12
k	2.2	2.3	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4
U (m/s)	7.1	4.4	5.3	11.5	12.4	5.3	6.2	7.1	8	8.9	9.8	10.6

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