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Urban wind potential analysis: Case study of wind turbines integrated into a building using on-site measurements and CFD modelling

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Abstract:

Energy solutions based in renewable energy sources are needed to overcome fossil fuel crisis due to supply uncertainties, increasing prices and climate changes. Innovative energy solutions for a sustainable and resilient energy system for the cities is required, special attention should also be paid greenhouse gases emissions. Wind energy systems integrated in to building in urban areas are a promising technological alternative. In this work an assessment of wind energy potential in a typical building in Santo Domingo, Dominican Republic was performed. The main idea is establish a methodology to explore how small wind turbines can be integrated in building to contribute to the energy sufficiency in urban areas. For this purpose, was developed a simple but robust framework to provide a city-environment assessment of the wind energy potential considering roof-mounted turbines. An especial distinction was made to capture the effect of the building geometry in the electricity generation using Computational Fluid Dynamic (CFD) modelling and the related in the energy production. The framework is based on seven main steps: (1) site selection, (2) resource prospecting/analysis including CFD, (3) turbine selection, (4) estimation of currently produced energy, (5) Environmental evaluation, (6) Resilience and Economic Analysis, and (7) System Installation. The urban wind energy potential was assessed considering one small two-blade Darrius H-type vertical axis wind turbines on the roofs of a 29 m high-rise buildings, yielding an annual energy production in the best site of about 1030 kWh with a potential CO_2 emission reduction of 0.64 Ton/yr. It was also found that the wind speed decrees significantly downstream the wind flow direction due to the building geometry, this means that the average speed could decrees in about 100% from the site of the wind flow incidence to the opposite, with the consequent impact in the energy generation.

Keywords:

Urban wind energy assessment; Distributed power system; Wind turbine; CFD.

1. Introduction

The world is undergoing an energy transition to limit climate change, the main base of such transition is accelerating the use of clean energy. Several of the United Nations Sustainable Development Goals until 2030 are set in this direction, especially Goal 7, which sets out the challenge of Affordable and Clean Energy for All [1]. For this purpose, it is necessary to reduce the costs of renewable energies and take full advantage of the potential of energy efficiency, digitalization, smart technologies and sustainable solutions for electrification [2]. This paper proposes the use of urban wind energy as one of the alternatives to decouple the necessary economic expansion from the intensive use of fossil fuels. The goal is to promote the idea of providing energy accessibility in a sustainable way for humanity, taking the Dominican Republic (DR) as a case study. In that way, the DR, in the frame of the Paris agreement has the commitment to reduce by 25% the estimated per capita emissions of 3.6 tCO_{2eq} by 2030, with respect to 2010 [3].

Due to the high population density in urban areas, both in emerging and developed countries, tailor-made energy solutions close to the area where demand is generated are required. Globally, consumption in buildings accounts for 30 % of primary energy consumption [4]. With the implementation of energy efficiency measures, savings about 20 – 40 % can be achieved. Small wind turbine (SWT) installations are expected to contribute to the energy transition towards low carbon and high efficiency services in cities [5]. Decentralized generation in urban environments is a possible solution, involving technologies such as solar PV and SWT [6]. In this direction, a full understanding of the renewable resources available in urban environments is needed. Tasneem et al. [7] argued that SWTs can be positioned in or around high-rise buildings, rail tracks, highways, and other

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urban sites. The estimated energy of the wind in these places becomes very complicated due to it being aerodynamically irregular and heterogeneous. The obstacles, such as buildings, trees, and others have an influence on wind turbulence [8]. These obstacles significantly reduce the use of the resource through SWTs due to those extract momentum from the wind flow, causing a lower average wind speed [9]. Building shape, height, and separation between itself influence wind flow and direction due to the turbulence and surface roughness produced by them [7]. A proper wind speed assessment, wind selection and installation are the most challenging goals to address. Wind flow around a building is complex, since a separation zone results and vortices generated, however, the main region of interest is where there is an amplification of the flow [10].

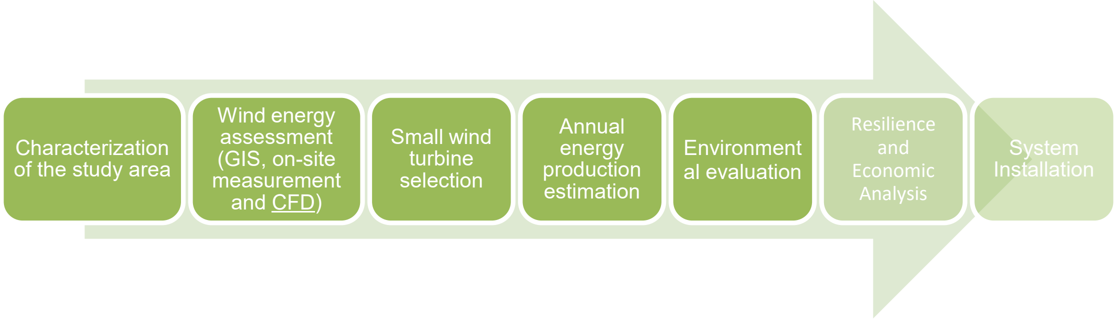
For the studies in the urban environment of wind potential the progress of Computational Fluid Dynamic (CFD) scope is a corner stone. CFD can be efficiently integrated in the urban wind energy assessments methods. These studies are in principle dedicated to characterizing air flow through obstacles, such as building and trees in a volume of control. In an urban location the flow is considered as turbulent. In this way should be used the Favre-averaged Navier-Stokes equations with SOLIDWORKS Flow Simulation software to model turbulent flows in the urban environment [11], [12].

A two-equation standard model k-ε is involved in the flow simulations because of its robustness and simplicity, more advanced turbulence models could be employed, however the k-ε model is accurate enough for the purpose of this work. The propose of this study is develop existing methodologies for better prediction of wind behaviour in urban environment and predict the energy potential of small wind turbines in microgeneration.

This research, rather novel in the Caribbean region and especially in the DR, aims to contribute to the characterization of wind in urban environments for the proper assessment of the technology to be used. The wind characteristics and the orography (existing buildings, terrain, etc.) are crucial elements for the deployment of SWT in urban environment. Another expectation of this work is to influence the architecture and urban planning to facilitate the use of the wind resource in the future. This research focuses on the potential of urban building in the DR, Santo Domingo for urban wind energy deployment. One building is studied in detail using CFD analysis in order to achieve the best performance of the wind energy technology.

2. Methodology

The methodology presented in this research have the purpose to perform with adequate precision a characterization of the urban wind energy potential in the Caribbean area, especially in the DR. It is important to highlight the efforts made to combine the current state of the art in the subject and the data available in the context of the region. In the literature consulted, very few studies of urban wind potential in tropical areas have been identified [13], [14]. However, worldwide scale there are many of such studies, important contributions has been made by authors such as AL-Yahyai, Bekele and Rezaeiha [15]–[19]. So far, no consistent research on the potential of urban wind in Caribbean cities has been identified in the consulted literature. In that way, a methodology is proposed to analyse the energy potential of urban wind. This methodology adopts several steps from some existing ones and proposes to incorporate an environmental evaluation and a detailed CFD analysis integrated to Geographic Information Systems (GIS) and on-site measurements. This adding lead to a wider study, taking into account the need to reduce the CO_2 emissions, define best site to install the wind turbine and predict accurately enough the annual electricity generation. The methodology includes seven steps: (1) site selection, (2) resource prospecting/analysis including CFD, (3) turbine selection, (4) estimation of currently produced energy, and (5) Environmental evaluation, (6) Resilience and Economic Analysis, and (7) System Installation as shown synthetically in Figure 1. The last two steps of the methodology are the Resilience and Economic evaluation and the Detailed Engineering of the final project; both are beyond the scope of this work. The step from 1 to 7 presented in Figure 1 are described in the following sections.



Characterization of the study area

Wind energy assessment (GIS, on-site measurement and CFD)

Small wind turbine selection

Annual energy production estimation

Environmental evaluation

Resilience and Economic Analysis

System Installation

Figure 1. Schematic illustration of the steps of the proposed methodology.

2.1. Characterization of the study area

There is great potential in the use of urban wind for distributed electricity generation in densely populated urban areas [20], [21]. In these environments, small wind turbines (SWTs) can be conceived as building-

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integrated from the design phase or installed on rooftops of existing buildings or surrounding areas. Distributed wind energy in cities has the advantage of its proximity to the point of electricity demand, which means reduced costs for high-voltage transmission lines as well as for the necessary devices of such a system [22].

Trees, buildings and other obstacles on the ground influence wind speed and turbulence, especially in sites with low wind speed and high turbulence levels [8]. This significantly reduces the resource utilisation using SWTs, obstacles extract wind flow momentum, resulting in lower average wind speed [9].

In order to identify potentially usable buildings for SWTs siting, parameters such as height, available roof area and structural integrity need to be assessed. A possible method for this purpose was identified in the work performed by Rezaeiha [18]. In this type of research, buildings in cities should identified and classified using GIS databases available on freely accessible websites, such as: [23]. These tools serve as a starting point to stratify buildings that meet the criteria for SWT installation. In this kind of research, in the case of Santo Domingo, buildings considered could be taken from the data base https://skyscraperpage.com/. In the case there is not existing database with information about the buildings an inspection must be carried out.

2.2. Wind energy assessment

In the literature several methods can be found for site-specific urban wind forecasting for energy purposes. The most commonly used methods are: on-site measurement, wind tunnel, numerical weather prediction, Computational Fluid Dynamic (CFD) and analytical methods [18], [24]–[28]. In any case, the main objective is to perform a wind characterization that includes the determination of parameters such as: average speed, direction, turbulence, energy density, etc. In this work, on-site measurements are used to evaluate the urban wind potential in the cities of Santo Domingo and, in DR. A brief description of this method is presented below.

2.2.1 On-site measurement

Wind speed and direction are the main parameters for the characterisation of the urban wind for energy purposes. The reference wind speed is established on the basis of measurements averaged every 10 minutes, according to the International Electrotechnical Commission standard. For the measurement of these parameters, an anemometer installed according to the aforementioned standard at the measurement site is needed [29]. In this study a data set collected from an anemometer installed in representative building in Santo Domingo were used.

Usually, the wind speed and direction are statistically processed and plotted on a polar diagram called a wind rose, where the radial axis indicates the magnitude and frequency of the wind, showing the prevailing wind direction. It can also be displayed in a Cartesian coordinate diagram [21], [30], [31].

The accumulated records of wind parameters allow the construction of probability functions and predict the energy potential. The Weibull, Rayleigh and Lognormal distributions are widely adopted to predict wind speed. The most widely used is the Weibull distribution because of its flexibility and simplicity. However, limitations have been observed in this function for average wind speed lower than 2 m/s or close to zero, in this speed range the density distribution estimation can be very inconsistent [17]. This limitation is not relevant to use this function evaluating the potential for SWT, because typically the cut-out speed of this machines is 2 m/s. In this work, the Rayleigh Distribution, a variant of the Weibull distribution with a form factor equal to 2 is adopted [29]. Weibull distribution $p(v)$ is the probability distribution function used to describe the distribution of wind speeds over time duration. The Weibull probability function is given by Eq. (1):

$$p(v) = \left(\frac{k}{c}\right) * \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}}, \tag{1}$$

Where k is the shape factor, a parameter that controls the width of the distribution and c is the scale factor in m/s, this parameter controls the average wind speed and is defined in Eq. (2).

$$c = \frac{V_{avg}}{\sqrt{\pi}}, \tag{2}$$

Where: V_{avg}, is the average wind speed.

The parameters k and c can be estimated by several methods, being the method of maximum likelihood the most commonly used (Karthikeya et al., 2016; Islam et al., 2011).

Another important characteristic of the wind is the Turbulence Intensity (TI), it is defined as the ratio of standard deviation of fluctuating wind velocity to the mean wind speed, and it represents the intensity of wind velocity fluctuation. This index should be calculated at 15 m/s, as it is one of the characteristic parameters included in the classification (classes) of SWTs according to the International Electrotechnical Commission [29]. At presents four SWT classes has been defined, for all classed the turbulence intensity should be 0.18 or less, and for the "S" class, it should be determined according to the referred standard. A turbine should not be exposed to wind turbulence intensity higher than 25 %, so this parameter is essential for determining the installation of small wind turbines [8]. Small wind turbines must be able to respond to frequent urban wind fluctuations and the site and system characteristics [32]. According to the National Renewable Energy

Laboratory (NREL) of the United States, turbulence levels can be categorised as follows: low, if TI have values less than or equal to 10%; moderate, if TI have values between 10% to 25%; and high, if TI have values greater than 25% [33]. The TI calculation is given by Eq. (3).

$$TI = \frac{\sigma}{V_{avg}} \tag{3}$$

Where: σ is the 10-min standard deviation, V_{avg} is 10-min average wind speed.

2.2.2. Computational Fluid Dynamic

Computational Fluid Dynamic (CFD) is a numerical simulation technique to study the behaviour of wind flow in urban locations. This method has become widely used due to advances in number methods and computational resources [34]. The CDF models have the ability to calculate the aerodynamic components with the integration of the Navier-Stokes equations at the periphery of the turbine blades [32]. The CFD is an efficient alternative to characterize the turbulence in the wind in the building. The method has been improved in simplification, calculation model, mesh processing, setting of boundary conditions, equation solver, simulation tools and other aspects [8].

The biggest barrier to the acceptance of CFD results is related to the accuracy of the technique, the costs, and the skill of the user. Verification and valuation is required for the CDF simulation results. Typically, the validation of CFD studies for real urban areas are carried out with field measurement data (Experimental tests) and wind tunnel [13], [28], [32], [34].

According to Mittal et al. [28], the accuracy of the CFD simulation strongly depends on the selection of the turbulence model. The capacity of each turbulence model and its precision for different analysis resolutions are reported in the literature based on the experiences of the researchers. With this method, important findings have been obtained, such as: the recommendation to install small wind turbines 1.4 m above the roof of buildings and if they are horizontal axis wind turbines, that they be installed in the middle of the roof, as well as installing the turbine as high as possible in the windward direction [35].

The proposed methodology for the development building wind turbines projects in an urban environment based on CFD analysis was summarized in the in the Figure 1. This methodology lead to a better estimation and reduced the time, cost and risk of the feasibility studies in the development of such projects.

As mentioned in section 2.1 it is necessary to delimit the project location and the surrounding zone to study the feasibility of the project. It is important to develop a general view aided by the CFD simulation to predict the flow patterns of the wind stream in the urban complex. With the purpose of assess the performance of the small wind turbines on the roof of the building of interest for the CFD simulations. After the site is selected, a standard wind resource assessment is completed, by using statistical and historical field data to estimate the power output of SWTs. The next stage is the CFD-based assessment, which includes four steps: the modelling site assessment, the modelling building-structure study, the modelling SWT study, and the modelling structure-SWT study. In these steps, a CFD model of the site that includes the building and the surrounding areas, is elaborated, as well as a model of the building or structure suitable for CFD analysis. This analysis will allow selecting the type of turbine to install. After the SWTs selection a performance study using CFD analysis should be conducted. The results of this final analysis using the integrated method will define the viability of the project regarding technical performance. In this study is adopted SOLIDWORKS Flow Simulation to evaluate wind behaviour using CFD and applying finite volume analysis [36].

2.3. Selection of small turbines

SWTs are aerodynamic machines, used to convert wind energy into electricity. Electricity production is a function of air density, the sweep area of the turbine blades, and the speed cube [37]. There is a wide variety of designs and types of small wind turbines. Commonly, highly efficient developments are considerably influenced by criteria related to the operation and location of the machine. In the wind turbine industry, there are mainly two designs, horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) [26], [35], [38].

HAWTs are generally installed in areas relatively separated from cities, and with considerable heights above ground level, according to local policies and regulations. These machines must always be oriented with the rotor perpendicular to the wind direction, which makes it unappropriated to be installed in places with frequent changes in wind direction or high turbulence [7], [10].

VAWTs can be classified into two main categories, Darrieus and Savonius rotor. Darrieus VAWTs are usually considered a lift rotor, since the torque is generated by the average lift force. On the other hand, Savonius rotors operate normally by the action of drag force. H-type rotor VAWTs are a combination of lift and drag forces. VAWTs are more used in urban environments because they are less vulnerable to changes in wind directions.

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According to the International Electrotechnical Commission (IEC), SWTs are those with a capacity ≤ 50 kW and a rotor swept area ≤ 200 m^2 [29]. Different classifications, according to power, hub height, and swept exist in different countries. In this work we adopt IEC classification.

According to Rezaeiha [18], urban wind energy harvesting systems can be categorized as follow: (i) Stand-alone near building, (ii) Retrofitted to existing building, and (iii) Fully integrated into building architectural form. In this work it is considered appropriate to use a small two-blade Darrieus H-type vertical axis turbine (VAWT). This machine is 1 m in diameter and 5 m in height, with a sweeping area of 5 m^2. This SWTs were selected because a good performance at low speeds and turbulent environments, which is a condition that generally occurs in urban areas.

2.4. Annual energy production estimation

For the estimation of the annual energy production (AEP), the methodology proposed by Rezaeiha [18] is adopted. The equation to estimate the AEP is shown in Eq. (4):

$$AEP = 8760 * \int_0^\infty P\left(V_{avg}; c; k\right) * P(V) dv \tag{4}$$

Where: 8760 are the hours during a year, $P\left(V_{avg}; c; k\right) *$ is the probability of occurrence of a given speed based on the Weibull distribution, and $P(V)$ is the power produced by the wind turbine at that speed. The power extracted by the wind turbine is described according to Eq. (5):

$$P(V) = 0.5 * C_P * \rho * A * {V_{avg}}^3 \tag{5}$$

Where: A is rotor area, C_P is the power coefficient of the rotor, V_{avg} is the wind speed and ρ is the air density.

2.5. Environmental evaluation

To evaluate the potential environmental benefit from the installation of the SWTs an assessment of the avoided CO_2 emissions from replacing electricity generation from fossil fuels by electricity from SWTs can be carried out. Fossil fuels prevail in DR electricity sector, according to Guerrero-Liquet: oil (46.27%), natural gas (25.92%) and coal (14.03%), represented 86% of electricity generation in the country. Only 10% of electricity generation is produced from renewable sources, particularly hydropower (6.26%) and wind energy (1.90%) [39]. Is it important to highlight that Oil and coal are the higher CO_2 emitters. With data from the Coordinating Body of the National Interconnected Electrical System (OC-SENI) an estimation of the emission factors for these fuels has been done [40]. It was found that emissions factors expressed in $kgCO_2eq/kWh$ for oil and coal are about 0.75 and 0.98 respectively. On the other hand, according to the Standardized baselines set by the United Nations Framework Convention on Climate Change, the CO_2 emission factor for the SENI in DR applicable to wind and solar power generation project activities is 0.6216 $kgCO_2/kWh$. This standardized baseline will be adopted for calculations in this research [41]. Assuming the SWT electricity generation carbon free, the Avoided Emission (AE) in $kgCO_{2eq}$ can be calculated by multiplying the annual energy production (AEP) in kWh, by Emission Factor (EF) in $kgCO_{2eq}/kWh$, as shown in Eq. (6).

$$AE = AEP * EF \tag{6}$$

3. Case study, results, and discussion

This work has been developed to stablish a methodology to assess the urban wind energy potential in buildings for the Dominican Republic, as a first case study a representative building located in the Technological Institute of Santo Domingo (INTEC) has been taken. The most important findings are presented from a survey campaign carried out at INTEC located in Santo Domingo. Two anemometers were installed for data recording, which are identified with the following nomenclature: Anem1-INTEC and Anem2-INTEC. The Santo Domingo Institute of Technology (INTEC) is a private, non-profit, public service, Dominican higher education institution founded in 1972 by a group of academics committed to the social transformation of the country and the continuous promotion of the quality of education. It is located in the coordinate 18°29'16.81"N, 69°57'45.18"W. A detailed map of the INTEC campus is shown in Figure 2.

The Anem1-INTEC and Anem2-INTEC registered data during the period May-December and June-December 2017 respectively. The sensors were installed in building with 20 m height. A total of 208881 and 152816 records were taken from Anem1-INTEC and Anem2-INTEC, with an availability of 71% and 77% respectively. In 2017 the country was hit by several meteorological adverse events which affected the data collection. Figure 3 a) shows the behaviour of the monthly average wins speed. The mean speed for the periods was about 2.50 m/s at 20 m. At 40 m height the estimated average wind speed using the Hellmann exponential law and the logarithmic wind profile law was 3.05 m/s. The Hellmann exponential is the general methods for estimating wind speeds at higher hub heights from known wind speed at lower heights [30].

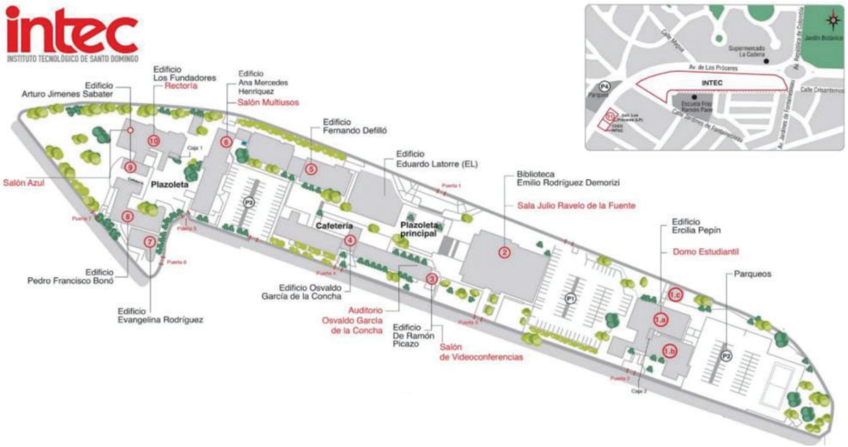

Figure 2. Detailed map of the INTEC campus.

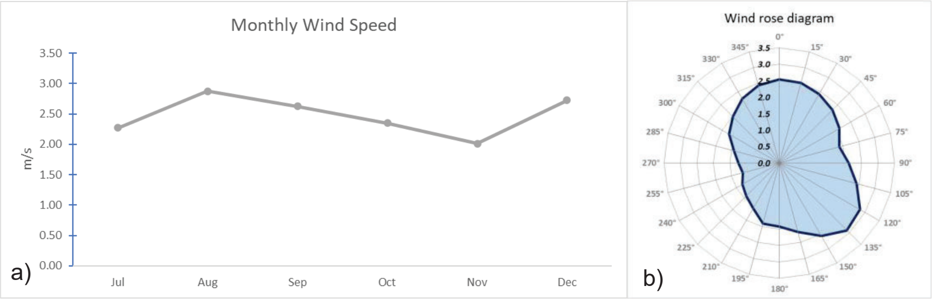

Figure 3. a) Average monthly wind speed, b) Period average wind rose.

Fig. 3b) shows the wind rose for the three sensors during the study period. The predominant wind direction is North-East, with a strong correlation with the data records of the meteorological services for both measurements sites [31]. The predominant wind direction with the highest intensity was registered from 15° respect to North.

Table 1 shows the hourly variation of wind speed (WS) for one day. Table 1 has a colour scale, where red represents unfavourable speeds and green favourable. Note that in the interval from 13:00 to 15:00 the highest energy potential occurs. This is very positive, since the energy consumption associated with air conditioning in this horary is considerable in tropical areas. Note that in Santo Domingo there are average wind speeds higher than 2 m/s during approximately 18h every day.

Table 1. Daily average variation of wind speed.

h	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WS	2.00	1.98	1.92	1.91	1.88	1.90	2.06	2.49	2.80	2.90	2.97	3.13	3.21	3.42	3.29	3.07	2.92	2.68	2.54	2.36	2.27	2.14	2.10	2.07

From the minute-by-minute recordings, the average speed was calculated for 10-minute intervals. The most probable speed recorded were 2 m/s, 3 m/s and 4 m/s with probabilities of occurrence of 24.5%, 24% and 17.7% respectively. Figure 4 shows the Weibull distribution for the parameters given in Table 2. For a mean wind speed of 3.05 m/s the corresponding parameters for the Weibull distribution are 3.44 m/s and 2 for the share factor and scale factor, respectively. TI was categorised as moderate, high and low to 63%, 29% and 8%, respectively. This may be mainly associated with the terrain orography, deeming that these measurements were made in a building in an urban environment.

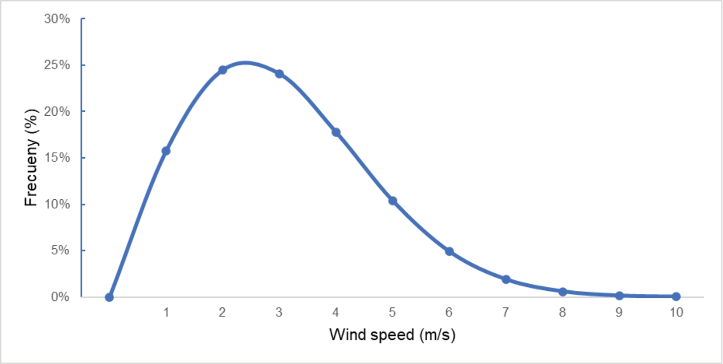

Figure 4. Weibull distribution.

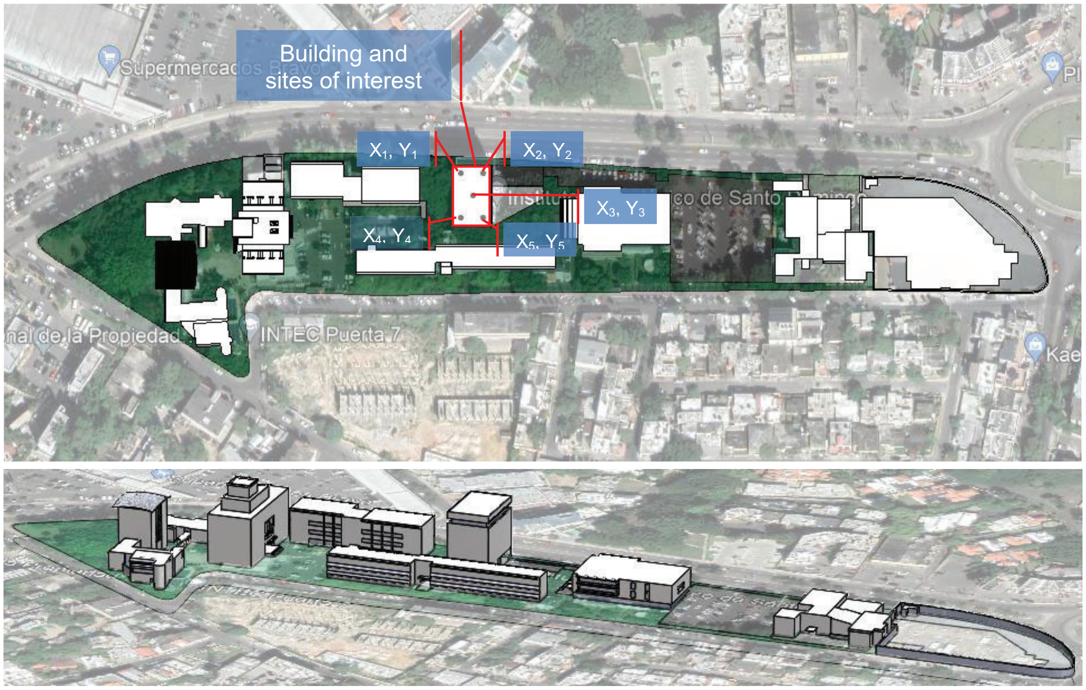

Figure 5. Physical model of the INTEC campus, building and sites of interest.

Table 2 Describes each one of the optimized initial conditions selected which correspond to the CFD simulations performed. The wall condition of 1,000,000 micrometres comes from "Guide to Meteorological Instruments and Methods of Observation", where it is pointed out that the roughness of the terrain is classified by the class of the terrain. INTEC is surrounded by class 7 terrain, presenting large regular obstacles typical of the suburbs, assigning it a roughness height of 1 m. The decomposition of each velocity parameter is represented at the Table 3.

The configuration of the grid and the determination of the size of the refinement of the mesh states the precision of which the CFD simulation will be performed. For these CFD simulation, a global mesh structured are selected with a manual refinement definition of 249 cells per X, 100 cells per Y and 100 cells per Z. This global mesh refinement exceeds the number of cells assigned in all axis by the highest level of auto refinement with the sole porpoise of ensure precision at the areas of interest. This results in 2,643,484 cells that integrate the meshing of which 78,416 are in contact with solids. Additional to the mesh refinement a control plane tool was employed to increase the density of cells at the areas of interest.

Table 2. Optimized Initial and boundary conditions for the development of CFD simulations.

Analysis type	Fluid Type	Boundary Conditions	Initial and Environment Conditions	Mesh Configuration
Flow Type: External. Gravity force: 9.81 m/s^2.	Air with all its physical properties. Laminar and Turbulent Flow.	Roughness length: 1,000,000 µm.	a)Thermodynamic parameters: -Temperature 28°C=301K. -Atmospheric pressure:101325 Pa. b) Velocity parameters: Wind speed of air 1 m/s, 2 m/s, 3 m/s, 4 m/s, 5 m/s, 6, m/s 7 m/s, 8 m/s, at 15°. c) Turbulence parameters: - Turbulence length: 0.4003m - Turbulence intensity: 0.1%. d) Humidity parameters: -Average relative humidity of 80%.	Manual Mesh with 2,643,484 control volume cells.

Table 3. Wind Velocity vector decomposition.

Magnitude (m/s)	Angle (degrees)	Velocity in X (m/s)	Velocity Y (m/s)
1	15°	-0.965926	0.258819
2	15°	-1.93185	0.517638
3	15°	-2.89778	0.776457
4	15°	-3.86370	1.03528
5	15°	-4.82963	1.29410
6	15°	-5.79555	1.55291
7	15°	-6.76148	1.81173
8	15°	-7.72741	2.07055

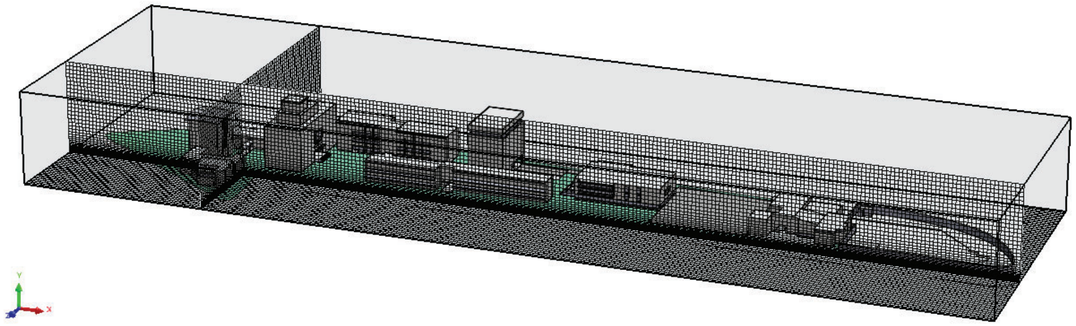

Figure 6. Dimetric view of the INTEC campus in SolidWorks Flow Simulation.

Figure 7 reveals the top view of velocity contour at 3 m/s at 15° of the INTEC was obtained by CFD simulations. Results shows how the wind is distributed across the campus and the high-speed zones over the tall buildings. The image below also reveals the possible positions to locate wind turbines over the EL building. Note in the Figure 7 how different is the wind speed in the different site of interest. From this observation can be deduced that energy generation of a wind turbine can be significantly different depending on the site of installation even over the same roof.

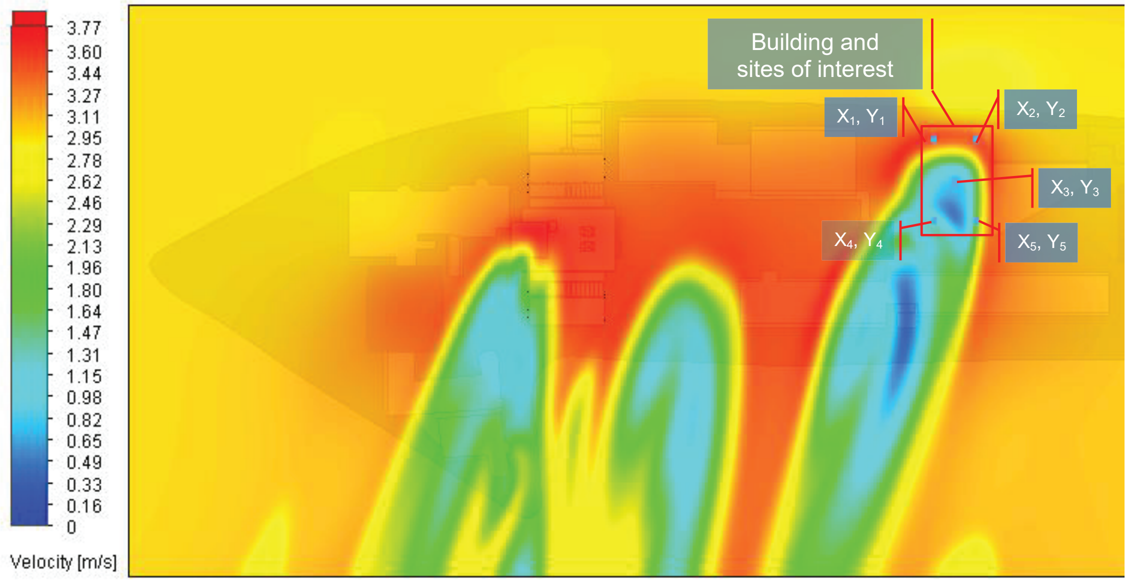

Figure 7. CFD simulation velocity contour at 34 m elevation, 3 m/s free stream flow.

The Table 4 summarise result of measurement analysis regarding the wind speed behaviour based on anemometers measurements collected near the building studied and wind behaviour analysed using CFD analysis.

Table 4. Wind speed information from anemometers and modelling results at sites of interest.

Free stream flow Wind speed (m/s)	Occurrence (hours)	Wind Speed at sites of interest from modelling (m/s)				
		X_1, Y_1	X_2, Y_2	X_3, Y_3	X_4, Y_4	X_5, Y_5
1	1380	1.1	1.1	0.1	0.4	0.3
2	2142	2.3	2.3	0.4	0.9	1.1
3	2106	3.5	3.5	0.6	1.2	1.8
4	1554	4.7	4.6	0.8	1.6	2.5
5	908	5.9	5.8	0.9	1.9	3.3
6	430	7.1	6.9	1.2	1.8	4.9
7	167	8.3	8.0	0.7	1.0	6.9
8	72	9.4	9.2	1.4	3.1	5.1

The Figure 8 shown how the wind speed may differ from one site to another even over the same roof.

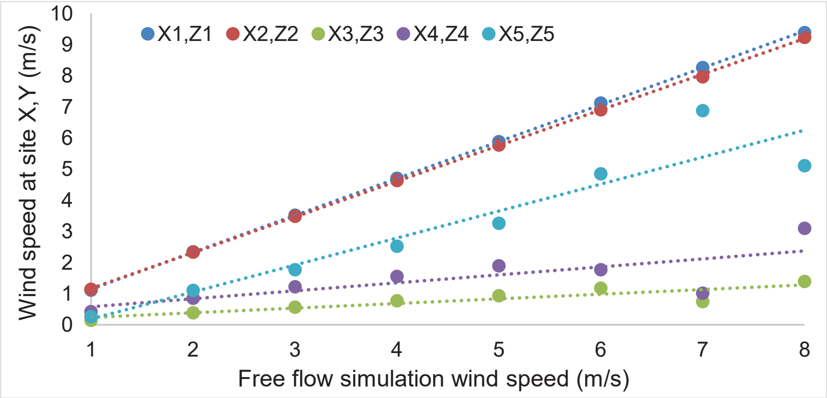

Figure 8. Wind speed at site vs. free flow simulation speed.

Given the wind characteristics described above, VAWT technology was chosen in this study, since this type of turbine have a good performance in urban locations with low wind speeds and high TI [18]. A turbine similar to the one selected by Rezaeiha in the wind potential studies in 12 cities in the Netherlands was selected [18]. The selected turbine is a Darrieus Type-H rotor with a rated power of 2.4 kW at a wind speed of 12.5 m/s and a swept area of 5 m^2. From the power curve of the Darrieus Type-H turbine, the energy produced during the year can be estimated as a function of wind speed regimes. The equation that best fit to the power curve for this machine was estimated using the potential regression method, with a correlation of R² = 0.9944, the function is given by Eq. (7):

$$y = 1.1501x^{3.0842} \tag{7}$$

Where: y, is the power delivered by the machine in Watt and x, is the wind speed in (m/s).

Table 5 shows the estimated annual power and energy generated for the given speed ranges of a VAWT installed at each sensor position, the energy that could potentially be generated at Anem2-INTEC position. Also, Table 5 shows the estimated annual power and energy generated for the given speed ranges of a VAWT installed at each sensor position, the energy that could potentially be generated at Anem2-INTEC position would be 1030 kWh/year.

Table 5. Power generation based on free stream speed and modelling results at sites of interest.

Speed (m/s)						Ocurr. (h/year)	Power (W)					
Free stream	X_1, Y_1	X_2, Y_2	X_3, Y_3	X_4, Y_4	X_5, Y_5		Free stream	X_1, Y_1	X_2, Y_2	X_3, Y_3	X_4, Y_4	X_5, Y_5
0	0	0	0	0	0	0	0	0	0	0	0	0
1	1.11	1.14	0.14	0.15	0.26	1,380	0	0	0	0	0	0
2	2.34	2.33	0.38	0.86	1.11	2,142	10	16	16	-	-	-
3	3.52	3.48	0.56	1.22	1.77	2,106	34	56	54	-	-	-
4	4.7	4.63	0.77	1.55	2.53	1,554	83	136	130	-	-	20
5	5.88	5.78	0.93	1.89	3.26	908	165	271	257	-	8	44
6	7.08	6.94	1.15	2.39	4.01	430	289	481	453	-	17	83
7	8.27	8.1	1.34	2.81	4.75	167	465	776	729	-	28	140
8	9.46	9.26	1.54	3.22	5.49	72	701	1175	1101	-	43	220

Table 6 shows the estimated annual energy generated for the given speed of a VAWT installed at each sensor position, the energy that could potentially be generated by one unit at X_1,Y_1 position would be 1,030 kWh/year. The avoided emissions CO_2 are also presented in Table 6.

Table 6. Power generation based on free stream speed and modelling results at sites of interest.

Parameters	Generated Energy (W-h/yr)					
	Free stream	X_1, Y_1	X_2, Y_2	X_3, Y_3	X_4, Y_4	X_5, Y_5
Annual energy per VAWT [kWh]	623	1,030	978	0	22	146
Avoided emissions CO_2 [kg/Year]	387	640	608	0	14	91
VAWTs	5	5	5	5	5	5
Total annual energy [kWh]	3,116	5,151	4,891	0	112	731
Total avoided emissions of CO_2 [kg/Year]	1,937	3,202	3,040	0	70	454

The Figure 9 is to illustrate how different can be the energy generation of a wind turbine depending on the site where this is installed even on the same roof. Based on the estimated annual energy production with an emission factor of 0.6216 TonCO_2/MWh, it can be determined that 0.640 tonnes of CO_2 emissions into the atmosphere per year could be avoided per SWT if it is located in the best site.

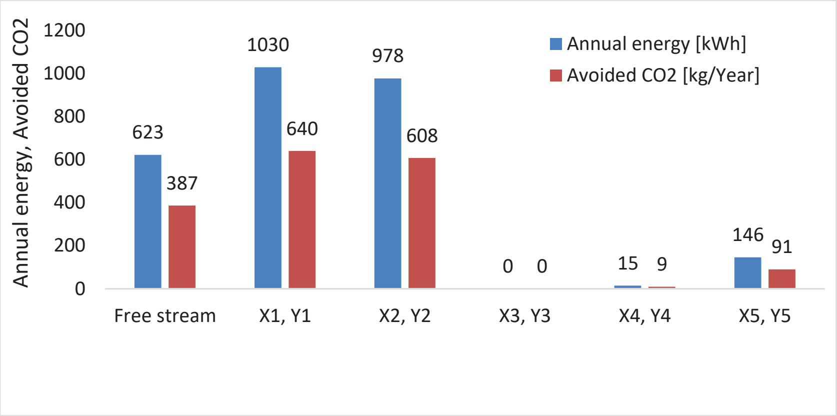

Figure 9. Annual energy generation and Avoided CO_2 emissions at site characterized by the anemometers and by CFD simulations.

4. Conclusions

This research is a starting point for assessing the urban wind potential for electricity generation in urban environment and contribute to the decarbonization of the Dominican Republic energy matrix. The wind generation potential in a typical building located in an urban area from Santo Domingo has been assessed. On-site measurement campaigns conducted at INTEC and simulation result analysis has been used.

The average wind speed in Anem1-INTEC, Anem2-INTEC was about 2.5 m/s respectively, which is considered a relatively low. At 40 m It was estimated an average wind speed of about 3.05 m/s. The prevailing wind direction with the highest intensity was recorded at 15° respect to North. The wind roses have good correlation with freely available GIS databases. Between 13:00h to 15:00h the higher wind intensity occurs.

A methodology was presented to estimate the wind potential in urban buildings taking into account the exact site of the SWT and the building geometry using, and integrated approach based on on-site measurements and CFD analysis. The selected turbine was VAWT Darrieus Type-H, with good performance at low speed and very turbulent environments. The estimated AEP for one turbine in best site was 1030 kWh/yr with a potential CO_2 emission reduction of 640 kg/yr. The site of the turbines even in the same roof is relevant for the energy generation, modelling results shown differences in the estimate energy generation from one corner of the roof to the opposite of 100%.

Future research should quantify 100% of the available potential in buildings with a detailed estimate of the number of buildings and the area available for VAWT installation. In addition, survey studies should be extended both spatially and temporally. Given the geographical position of the DR and its exposure to adverse meteorological events, a resilience and feasibility analysis will be performed for future urban wind potential analysis.

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