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CFD Design of Urban Wind Turbines: A Review and Critical Analysis

Christian V. Rodriguez*‡, Alberto Ríos**, Jaime E. Luyo*

*Faculty of Mechanical Engineering, National University of Engineering, Lima, Peru

** Faculty of Systems, Electronics and Industrial Engineering, Technical University of Ambato, Ambato, Ecuador

(cvrodriguezd@uni.pe, alrios13@hotmail.com, jeluyo@yahoo.es)

‡ Corresponding Author; Christian V. Rodriguez, Peru, Tel: +51 956 806 671,

cvrodriguezd@uni.pe

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Abstract- The Urban Wind Turbine (UWT) industry has experienced diverse results with some positive outcomes and various negative ones. Regarding negative outcomes, designers have often overestimated performances of UWTs. Differences of 20% or less between actual energy produced and energy originally estimated were found in literature. These differences would have been caused by an incorrect location of the UWTs. Note that determining the optimal location for UWTs is a complex task due to unforeseen wind behaviour found in urban environments. To cope with this complex task, Computational Fluid Dynamics (CFD) approach is presented as a suitable alternative. Thus, this paper aimed to develop a review to introduce recent advancements in the field of CFD design of UWTs, and to perform a critical analysis of these advancements. Accordingly, a Systematic Literature Review (SLR) associated with the topic was performed to obtain suitable information (primary studies) for the critical analysis. The results showed that the maximum velocity amplification factor, power coefficient and torque coefficient found in the primary studies were 1.8, 0.4627 and 0.4195, respectively. Note that these values were obtained using novel UWTs and wind amplification devices. Regarding CFD modelling, the standard k–ε turbulence model was the most used (42% of studies).

Keywords- Computational fluid dynamics; Urban wind turbines; Wind energy; Systematic literature review.

1. Introduction

Incorporation of renewable energies in power generation is promoted worldwide to reduce greenhouse gases emissions produced from fossil fuels combustion [1] [2], which cause degradation of public health [3]. Additionally, renewable energies have other benefits as diversifying energy resources, serving with energy to countries without fossil resources, enhancing the energetic systems structure, contributing to sustainable development, and increasing employment where renewable energy projects take place [4]. Note that renewable energy is the best alternative to reduce fossil fuel consumption [5].

Within renewable energies, hydro, solar and wind are the most popular. Note that hydro and wind are secondary sources of solar energy [6]. A drawback of power generation using hydro energy is the need of building water reservoirs which cause inundation of living beings' terrestrial habitat [7]. Regarding solar energy, this is only available during some hours per day. Meanwhile, wind energy is available all the day with different intensity. Thus, wind energy represents a reliable alternative for power generation.

Wind energy is harnessed using wind turbines classified as large and small. Large wind turbines are used in wind farms located in remote places far from urban zones. Conversely, small wind turbines can be installed in urban environments (i.e., Urban Wind Turbines, UWTs) to partially supply residential and commercial loads.

Blade Element Momentum (BEM) is the most widely used theory to predict loads and performance of wind turbines [8]. Note that BEM theory is suitable for designing wind turbines that operate in uniform flow as those installed in remote places. On the other hand, the use of Computational Fluid Dynamics (CFD) approach has become a common practice to research in the wind energy field. CFD has also helped designers to create more efficient wind turbines in the past [9]. Note that CFD requires a computational capacity higher than BEM, which shows lower accuracy compared to the former.

Particularly, the design of UWTs requires taking into account unforeseen conditions as different turbulence levels, and wind velocities and directions found in urban environments. These conditions can be appropriately simulated by means of CFD providing more accurate data of wind characteristics around both wind turbines and buildings compared to other numerical approaches [10]. CFD simulations allow achieving suitable wind turbine designs which is a key factor for the stable operation of these turbines [9]. Note that the study of wind characteristics is important for the evaluation of wind resources [11].

Additionally, the use of the CFD approach to predict wind behaviour in urban environments is more feasible than experimental approaches in the current context, as it is now difficult to move equipment and people to places where is necessary to measure the wind potential, which is vital in determining the power output of wind turbines. Conversely, computational tools as CFD can be easily accessed via the internet. Note that difficulties related to the current context can increase the costs of wind projects.

Some reports about wind projects as WINEUR [12], which aimed to determine the viability of UWT implementation in urban environments, were performed in the past. The UWTs evaluated in the WINEUR project had a rated power output between 1 and 20 kW. The authors mentioned that it is complex to determine the optimal location for UWTs due to unforeseen wind behaviour found in urban environments. Additionally, some case studies related to projects of UWTs were analysed by Fields et al. [13]. In this work, it was concluded that UWTs industry has experienced diverse results, with some positive project outcomes and several negative ones for stakeholders. In the projects with positive outcomes, wind turbines were placed on taller buildings relative to surrounding obstacles. Conversely, project feasibility of UWTs was not enough and not well defined. UWTs performance was also overestimated due to the fact that the values of actual energy produced and energy originally estimated differed by 20% or less.

Regarding UWTs integrated into tall buildings, we have the Bahrain World Trade Center, which is a 240 m height and 50-story twin tower. The Bahrain World Trade Center was designed to use wind energy passing through three-blade HAWTs with diameters of 29 m and capacities of 225 kW, which were installed at the bridges connecting the twin towers. The building was designed to generate between 11% and 15% of the electrical energy consumption [14]. Moreover, the Pearl River Tower is a 309 m height and 71-story building that was designed to increase the wind speed via the nozzle effect. A total of four 8 m height VAWTs are installed in four openings inside the building [15]. Furthermore, the Strata SE1 is a 148 m height and 43-story residential building with three HAWTs of 19.5 kW capacity each one located at the top of the tower. The turbines were expected to generate at least 50 MWh of electricity per year, which is about 8% of the total energy consumption of the building [16].

As seen before, the design and placement of small wind turbines in urban environments have been studied in recent decades. In this sense, Clausen and Wood [17] reviewed the advances in wind turbine technologies and they concluded that new methods for designing wind turbine blades would increase their performance. Ishugah et al. [18] also reviewed the wind turbine technologies, wind behaviour, wind resource assessment, and economic, social and environmental benefits of wind energy harnessing in urban environments. They concluded that wind turbine technology used in urban environments is a new field of study where novel ideas have been developed for sustainable exploitation. Additionally, a review of blade design, control and manufacturing of small Horizontal Axis Wind Turbines (HAWTs) were presented by Tummala et al. [19] who also categorised Vertical Axis Wind Turbines (VAWTs) based on experimental and numerical studies. More recently, Anup et al. [20] reviewed studies related to UWTs technology to understand the features of their performance, and identify the gaps in the field of knowledge. They concluded that reductions of 25%-35% in wind turbine performance could be attributed to high turbulence intensity levels of 18% or greater. The authors also investigated whether the use of the international design standard IEC 41400-2 for small wind turbines is valid for urban applications. They found that the wind models incorporated in the standard are not suitable for the installation of UWTs.

Ghasemian et al. [10] reviewed recent works related to CFD simulations of Darrieus VAWTs and presented recommendations for turbulence modelling, numerical schemes, and computational domain features. Parameters as tip speed ratio, wind velocity, solidity (σ), and blade characteristics were also investigated. The authors concluded that incoming flow is skewed and fluctuating due to the presence of buildings and other obstacles found in the urban environments. Furthermore, Kumar et al. [21] highlighted the main developments of VAWTs focusing on the integration with the urban environment. The authors concluded that further research is critical in making VAWTs a viable energy generation technology for decentralized energy applications.

Investigation results of wind energy applications including wind aerodynamics and wind flow over buildings were reported by Ayhan and Sağlam [22]. The authors concluded that CFD has to be used to model annual wind flows over and around the buildings to find the best location and design of wind turbines in the urban environment. Toja-Silva et al. [23] depicted a review on CFD applied to urban wind energy exploitation. Their work contained technical CFD aspects related to building aerodynamics applied to urban wind energy. The authors concluded that few simulations of wind turbines installed on building roofs were performed using wind turbine models. They also concluded that the power coefficient (Cp) of ducted wind turbines can be ten times higher than in open field conditions. Wong et al. [24] reviewed various flow augmentation systems, i.e., amplification systems, to provide information about current augmentation devices integrated with building structures. The authors highlighted that some augmentation systems were able to increase the maximum power output by up to 910% at a 6 m/s wind speed.

On the other hand, we have Systematic Literature Reviews (SLRs) which are a means of identifying and evaluating available research relevant to a particular topic [25]. Regarding wind turbine SLRs, most of them were related to the healthcare field as shown in [26], [27], which explored the relationship between wind turbine noise and visibility on local residents' health, respectively. Results in [26] suggested that wind turbine noise may be associated with sleep problems. Meanwhile, results in [27] indicated that visual exposure to wind turbines increased the sleep disturbance of local residents.

SLRs about wind power generation [28] and barriers to onshore wind energy implementation [29] were developed in the past. In the former, authors used 18 keywords to search scientific literature related to the topic. During the search, 2825 articles were found. Then, 145 articles were selected for the final analyses. With regard to the study of barriers to onshore wind energy implementation, 9367 articles were identified. After reading the articles, 477 articles were considered as containing relevant information for the SLR. More recently, Nunes et al. [30] performed a SLR of diffuser-augmented horizontal axis turbines. In this SLR, 426 studies were found, and 155 were used in the final analyses. The authors found that diffusers tended to narrow the Cp curves, reducing their optimum operational interval. The authors also advised that the diffuser-augmented turbine should be designed considering a simultaneous diffuser-rotor optimization.

To sum up, the UWT design is a new field that needs to be further studied to obtain an insight into the suitable turbines that works well under the unforeseen and skewed wind behaviour that can generally degrade the power performance of the turbines. In this sense, the CFD approach is a powerful tool to assess the wind energy potential and wind turbine behaviour operating under urban wind conditions. Thus, it is needed to study the CFD design of UWTs. In turn, the main objective of this study was to develop a review to introduce recent advancements in the field of CFD design of UWTs and to perform a critical analysis of these advancements. Accordingly, to achieve the main objective, a SLR associated with the CFD design of UWTs was performed to obtain suitable scientific literature to analyse and discuss in this work. In the SLR, the following Research Questions (RQs) were proposed:

RQ1: ¿What are the stages of the CFD design of urban wind turbines?

RQ2: ¿What are the models and methods used in the CFD design of urban wind turbines?

RQ3: ¿What are the main variables analysed in these studies?

RQ4: ¿What are the research tendencies?

The answer to these RQs gave us an insight into the state-of-the-art and future trends in the field of CFD design of UWTs. Note that this work pointed out building mounted and building integrated wind turbines.

Thus, the methodology used to develop the SLR was depicted in Section **Error! Reference source not found.**. Then, the answer to the RQs (Section **Error! Reference source not found.**) was presented in the same order as how they have proposed above. The research questions were presented in a logical order, from the recognition of the CFD design stages, passing through the models, methods and variables used in the primary studies, and ending with the identification of research tendencies. The answer to these research questions leads to the approach of future works (Section **Error! Reference source not found.**) and finally the presentation of the conclusions (Section **Error! Reference source not found.**).

2. Methodology

SLR is a vital characteristic of academic research [31]. SLRs can serve to review the background for an empirical study or a standalone part [32]. The first one is used to provide theoretical information or to detect a gap in the knowledge related to the field of study. On the other hand, standalone reviews try to make sense of a part of scientific literature via the integration of known research.

As stated by Kitchenham [25], one difference between a SLR and a conventional literature review is that the SLR starts by defining a review protocol that specifies the methods that will be used to perform the review. Therefore, the methods used to search, select, analyse and synthesize useful information needed to answer the RQs are presented below.

2.1. Search Strategy

The search for scientific literature related to the topic was carried out using electronic databases and a manual search.

The electronic databases included Scopus and Web of Science. This search was performed using representative words found together in articles' titles, abstracts and keywords. These representative words applied to the electronic databases were:

("CFD" OR "computational fluid dynamics" OR "numerical" OR aerodynamic) AND (assessment OR design OR analysis OR study OR methodology) AND ("wind turbines" OR "wind turbine" OR "wind energy" OR "wind technology" OR "urban energy" OR "urban wind") AND ("urban environment" OR "urban area" OR “city” OR “cities” OR "building integrated" OR "building-mounted" OR "roof-mounted" OR "building-roof")

As seen above, the first group of words represented the numerical and aerodynamic nature of this study approach. The second group took into account the type of approach used. The third one included synonyms and words related to wind turbines and wind energy. Finally, the last group referred to the location and placement of wind turbines.

Regarding manual search, repositories of theses and dissertations (grey literature) were considered.

2.2. Inclusion Criteria

This study was restricted to articles and theses (primary studies) written in the English language. Articles published only in peer-reviewed journals and theses available online from 1st January 2000 until 27th March 2020 were considered. Review articles were not included in the SLR analyses. Primary studies related to the CFD design of UWTs were included. These studies presented at least two stages within a design process of UWTs which include validation or verification, wind potential assessment, wind turbine design, electrical system modelling and grid integration. Note that the wind potential assessment took into account the wind behaviour found in urban environments. Those primary studies that analysed only either wind resource assessment or wind turbines features were excluded.

2.3. Studies Selection

The selection of primary studies consisted of two parts. The first part included only analyses of articles' titles and abstracts found in the search of primary studies. During these analyses, several studies which did not satisfy the inclusion criteria were discarded. In the second part, those studies which were not discarded in the previous part were read and analysed in their entirety. All information needed to answer the four RQs was extracted in this part.

The analyses were performed by one reviewer (CVR) and corroborated by another reviewer (AR). In case of lack of consensus on whether an article or thesis should be included in the final review, a third reviewer (JEL) was consulted.

2.4. Data Extraction and Synthesis

For all primary studies analysed in their entirety, the reviewers (CVR and AR) extracted systematically relevant information. Dataset extracted from primaries studies were synthesized and depicted in tables and figures as seen in Section **Error! Reference source not found.**. The critical analyses were performed by two reviewers (CVR and AR) and reviewed by another reviewer (JEL). These critical analyses included the information gathered from the SLR and other information from the scientific literature.

3. Results

3.1. General Information

Using the search strategy, 247 articles were found in Scopus and 161 in Web of Science (408 in total). Additionally, 2 theses were included in this study. After excluding duplicates, 286 primary studies remained. In the first part of the studies selection, studies' titles and abstracts analyses were only performed using the inclusion criteria detailed in Section **Error! Reference source not found.**. After the analyses, 24 studies for full-text reading were obtained as seen in **Error! Reference source not found.**. Note that these 24 studies came from 19 sources.

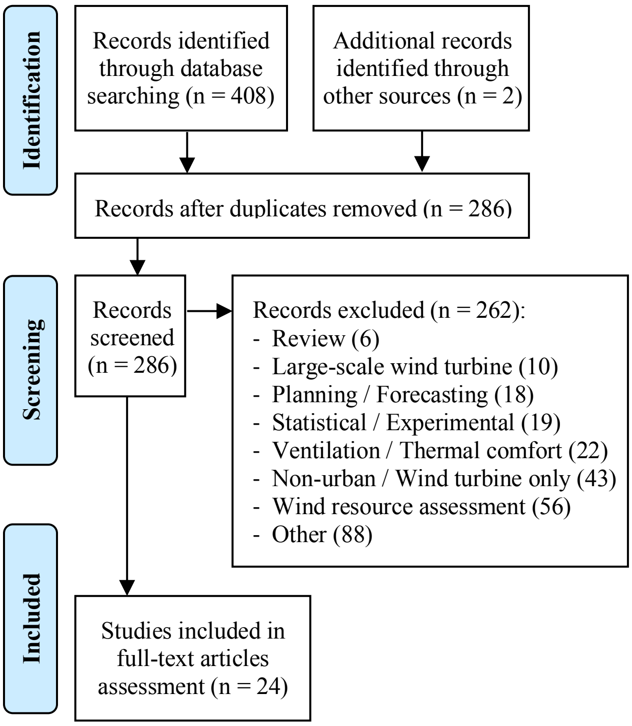


Fig. 1. PRISMA Flow Diagram adapted from [33].

The main reasons for excluding the 262 articles are listed in **Error! Reference source not found.**. Particularly, 6 articles corresponded to review papers and 10 studies corresponded to large-scale wind turbines located in isolated zones. Also, 18 articles containing planning/forecasting studies were excluded. Statistical analysis refers to Weibull parameters analyses were also excluded. Note that a considerable number of excluded studies corresponds to articles regarding only either wind turbine design or wind resource assessment being these 43 and 56, respectively. Additionally, other brand mainly contains solar energy, anthropogenic heat, aerofoils, surface energy balance and feasibility analyses.

The selected studies were published between 2007 and 2020, as seen in **Error! Reference source not found.**. Overall, there were not many studies associated with the CFD design of UWTs. Note that the number of studies on the topic has increased in recent years. This could be due to the recent development of processors with greater computational power, which makes it possible to work with more complex numerical models. Last year, only a study was presented in **Error! Reference source not found.** due to the deadline of the search was 27th March 2020. It would be expected that more articles will be published during 2020.

Additionally, **Error! Reference source not found.** was constructed based on the number of citations including the 24 studies of the SLR, see **Error! Reference source not**

found.. According to this, the articles of Balduzzi et al. [34] and Chong et al. [35] showed the highest number of citations coming from both the same source (Applied Energy). Also, the study of Heath et al. [36] (Wind Energy) depicted a relatively high number of citations. They represented about 60% of the total number of citations. More detail of the article's findings will be presented in the following subsections.

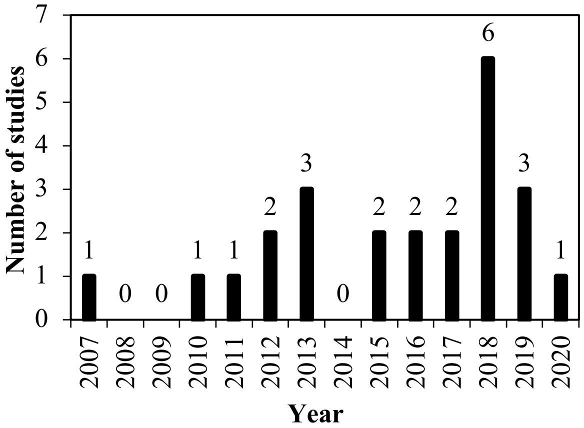


Fig. 2. Citation frequency of primary studies.

3.2. RQ 1: Stages of CFD Design

Since efficiency in costs and calculation time at the design stages of machines is essential in the wind turbine industry [37], it is necessary the identification and detailed analysis of those design stages. In turn, within the primary studies analysed (listed in **Error! Reference source not found.**), different design stages were found and explained below:

- Wind data: It consists of gathering and processing wind velocity and direction data, which are measured near a zone of interest.
- Validation: First, a mesh independence study is carried out to determine the number of mesh elements of the computational domain, which can include the urban environment and or the UWTs. Then, a comparison of numerical and measurement results is performed to know the agreement between them.
- Wind resource assessment: Urban environment simulation (including UWT or not) is performed to find the best place to installed the UWT and or to determine the wind energy potential.
- Wind turbine design: It consists of determining or selecting the UWT geometry and features.
- Potential assessment: Calculation of the wind turbine power output for the specific urban environment conditions.
- Electrical system modelling: Numerical modelling of the UWT electrical system needed to supply a load or integrate with the electrical grid.

As seen in **Error! Reference source not found.**, the stages that contained CFD calculations were validation, wind resource assessment, and wind turbine design. Note that gathering and processing additional information needed to model and simulate the UWT, urban environment and electrical system were implicitly included within the aforementioned stages.

The design stages contained in the primary study are shown in **Error! Reference source not found.**.

Table 1. Citations' ranking.

Rank	Article's author	Source	Number of citations
1	Balduzzi et al. [34]	Applied Energy	146
2	Chong et al. [35]	Applied Energy	79
3	Heath et al. [36]	Wind Energy	78
4	Balduzzi et al. [38]	Renewable Energy	46
5	Park et al. [39]	Energies	21
6	Larin et al. [40]	Journal of Wind Engineering and Industrial Aerodynamics	16
7	Krishnan and Paraschivoiu [41]	Sustainable Cities and Society	15
8	Dilimulati et al. [42]	Journal of Wind Engineering and Industrial Aerodynamics	14
9	Bianchi et al. [43]	Journal of Turbomachinery-Transactions of the Asme	13
10	Arteaga-López et al. [44]	Energy	9
11	Colley [45]	University of Huddersfield	6
12	Guerri et al. [46]	Wind Engineering	6
13	Hang et al. [47]	International Journal of Precision Engineering and Manufacturing-Green Technology	6
14	Hassanli et al. [48]	Journal of Wind Engineering and Industrial Aerodynamics	6
15	Riva [49]	Politecnico Di Milano	5
16	Zhu et al. [50]	Journal of Renewable and Sustainable Energy	5
17	Soebiyan et al. [51]	Chemical Engineering Transactions	4
18	Cho et al. [52]	International Journal of Technology	3
19	Kim et al. [53]	Remote Sensing	3
20	Jafari et al. [54]	Journal of Wind Engineering and Industrial Aerodynamics	2
21	Li et al. [55]	Advances in Mechanical Engineering	1
22	Abu-Thuraia et al. [56]	Transactions of the Canadian Society for Mechanical Engineering	0

23	Jafari et al. [57]	Energy Science & Engineering	0
24	Shiraz et al. [58]	Sustainable Cities and Society	0

The wind data used was mainly related to wind measurement databases of specific places modelled in the primary studies. Note that conventional techniques for estimating wind features involve installing anemometers and measuring wind speeds for up to a year [36]. The wind measurements are usually performed by institutes, universities, and meteorological centres, which only present the measurements of specific points, but not detailed wind field measurements of an area within a city as in [59]. Note that the detailed field measurements could be important to validate numerical models in the validation stage. Conversely, Kim et al. [53] carried out a remote sensing campaign for two months to obtain wind data of Seoul, Korea. This data was extended to one-year data. Lidar and Sodar remote sensors were employed. On the other hand, some authors did not mention their wind data sources as seen in **Error! Reference source not found.**.

In the validation stage, numerical results were mainly compared with wind tunnel measurements, which include wind velocities, pressures, torque, and dimensionless coefficients. Particularly, three authors did not show their validation results. Note that numerical results of a study could lose veracity if authors do not clearly present the validation stage results. It is also observed that there would not enough wind measurements to fully validate wind behaviour numerical results in urban environments.

Within the wind resource assessment stage, most authors (50% of the studies) simulated only a single building for their analyses. Meanwhile, Zhu et al. [50] took into account two buildings. Also, some authors deemed building arrangements to study the wind flow behaviour. Conversely, other authors regarded a full urban environment (29%) which showed a wind flow behaviour more realistic than the aforementioned arrangements.

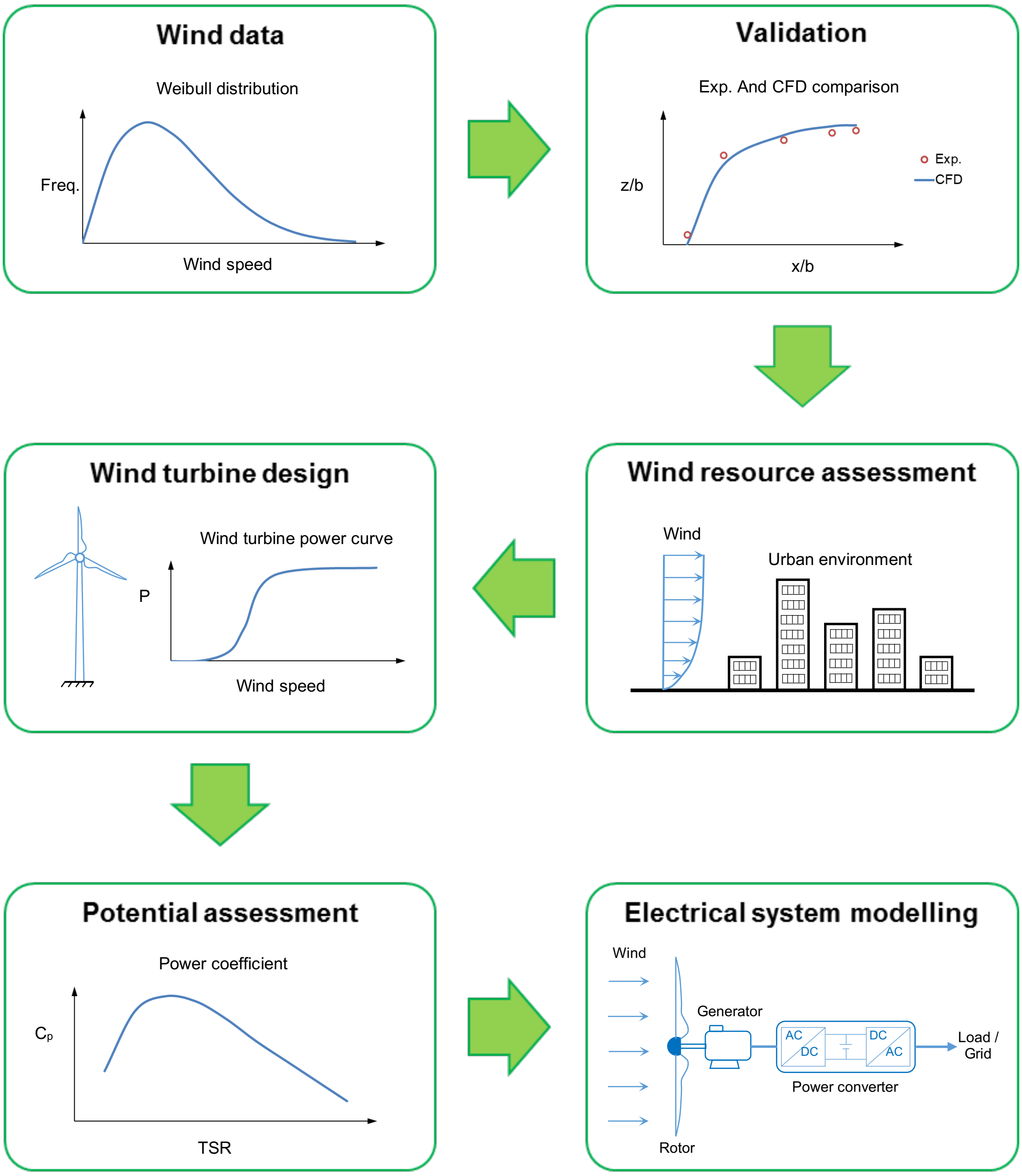


Fig. 3. Diagram of design stages of UWTs.

Note that in all the primary studies, geometrical simplifications of urban environments were performed which would affect the wind flow modelling as shown in [60]. As depicted in **Error! Reference source not found.**, it was not considered the wind resource assessment stage for Chong et al. [35], since they only considered a part of a single building in their experiments but not in their numerical simulations.

With regard to wind velocities, authors mainly used one wind velocity at a specific height as a reference to compute an atmospheric boundary layer by means of power or logarithmic law, which do not represent a real wind behaviour and can affect the wind flow modelling and modify the energy potential values of a specific place. Similarly, most authors preferred to simulate only a main wind direction. Conversely, Hassanli et al. [48], Zhu et al. [50], and Jafari et al. [57] simulated many wind directions to have a whole spectrum of the wind potential. Particularly, Soebiyan et al. [51] considered wind velocities and directions depending on seasons which represent a more realistic condition.

It is clear that wind turbine selection was preferred (71%) over design. It responds to the objective of each study. In particular, studies aimed to achieve a better wind turbine performance chose design instead of selection. Conversely, the selection was chosen when energy output and velocity amplification factor (Af) analyses were the main objectives. Note that the skew angle can modify the Cp of the wind turbine, so, the selection of the turbine typology is significantly relevant in defining the final energy harvesting [38]. In the case of Cho et al. [52], since they only calculated the Af without considering a type of UWT, so the wind turbine design stage was not taken into account for them (see **Error! Reference source not found.**).

The potential assessment stage included Af, Cp, torque coefficient (Ct), and energy output calculations. More detail of the results of this stage will be discussed in Section **Error! Reference source not found.**.

Table 2. Design stages of urban wind turbines.

Author	**Wind data**		**Valid.**	**Wind resource assessment**				**Wind turbine design**		**Potential assessment**	**Electrical system modelling**
	Measured	**Database**		**Single build.**	**Two build.**	**Buildings arrange.**	**Urban environ.**	**Selection**	**Design**		
Balduzzi et al. [34]		X	X				X	X		X	
Chong et al. [35]		X	X					X		X	
Heath et al. [36]		X	X			X		X		X	
Balduzzi et al. [38]		X	X			X		X		X	
Park et al. [39]		X	X	X					X	X	
Larin et al. [40]			X	X					X	X	
Krishnan and Paraschivoiu [41]			X	X					X	X	
Dilimulati et al. [42]		X	X				X		X	X	
Bianchi et al. [43]		X	X			X		X		X	
Arteaga-López et al. [44]		X					X	X		X	
Colley [45]		X	X	X				X		X	
Guerri et al. [46]			X	X				X		X	
Hang et al. [47]		X	X	X				X		X	
Hassanli et al. [48]		X	X	X				X		X	
Riva [49]							X	X		X	
Zhu et al. [50]		X	X		X			X		X	
Soebiyan et al. [51]		X	X				X	X		X	
Cho et al. [52]				X						X	
Kim et al. [53]	X		X				X	X		X	
Jafari et al. [54]		X	X	X					X	X	
Li et al. [55]		X	X	X					X	X	X
Abu-Thuraia et al. [56]			X	X					X	X	
Jafari et al. [57]		X	X	X				X		X	
Shiraz et al. [58]		X	X				X	X		X	

Note that reliable and consistent data about the performance of UWTs in actual urban environments is still limited [42]. Also note that the structural adaptability of UWTs to urban environments has yet to be tested [34].

Regarding the electrical system modelling, only Li et al. [55] modelled it using MATLAB, including both a Senegal-type wind turbine and a photovoltaic array as generators. Note that the authors considered supplying a local load without interconnection with the electrical grid.

Since effects on the electricity supplied by UWTs in the distribution system is a problem still not addressed [44], it could be a future work, i.e., incorporating electrical studies of a distribution system when wind turbines are added to the system, as an additional stage.

Overall, there is a necessity for more integrated design approaches as stated in [61], since the studies analysed here did not take into account others research fields within their design stages, which are important to the suitable design of machines as economic and structural analyses.

3.3. RQ 2: Models and Methods

Wind conditions in urban environments can change significantly depending on the buildings' shape, CFD simulation is therefore needed to accurately analyse the effect of buildings on wind conditions [53]. It is also important to correctly determine the initial conditions of the variables that will be used during the CFD simulations to have reliable numerical results in the CFD analyses [44]. Thus, the analyses of models and methods offer an opportunity to determine the most suitable configuration to solve the specific problem of UWTs operating in urban environments. In turn, the models and methods used in the primary studies, and their associated CFD parameters are shown in **Error! Reference source not found.**.

Table 3. Models and methods.

Author	Software	Model	Dimension	Max. build. height (m)	Turbulence model	State	Wind turbine modelling
Balduzzi et al. [34]	OpenFOAM	Building	2D	54.4 and 27.2	Standard k–ε	Steady	-
Chong et al.[35]	Fluent	Turbine	2D	-	SST k-ω	Transient	Sliding mesh
Heath et al. [36]	CFX	Building	3D	10	Standard k–ε	Transient	-
Balduzzi et al. [38]	OpenFOAM	Building	2D	54.4 and 27.2	Standard k–ε	Steady	-
Park et al. [39]	Fluent	Building/turbine	2D	5	Standard k-ω	Steady/Transient	Sliding mesh
Larin et al. [40]	Fluent	Building/turbine	2D/3D	30.48	Realizable k-ε	Transient	Sliding mesh
Krishnan and Paraschivoiu [41]	Fluent	Building/turbine	3D	30.48	Realizable k-ε	Transient	Sliding mesh
Dilimulati et al. [42]	Fluent	Building	3D	28.45	Realizable k-ε	Steady	-
Bianchi et al. [43]	OpenFOAM	Building	2D	54.4 and 27.2	Standard k–ε	Steady	-
Arteaga-López et al. [44]	Solidworks	Building/turbine	3D	-	Standard k–ε	Steady	-
Colley [45]	Fluent	Building/turbine	2D/3D	5.5	Standard k–ε	Steady/Transient	Multiple reference Frame / Sliding mesh
Guerri et al. [46]	-	Building	3D	9.1	Standard k-ω	Steady	-
Hang et al. [47]	Fluent	Building/turbine	2D	10.2	SST k-ω	Transient	Sliding mesh
Hassanli et al. [48]	Fluent	Building/turbine	3D	180	SST k-ω	Steady	-
Riva [49]	OpenFOAM	Building/turbine	3D	-	Standard k–ε	Transient	-
Zhu et al. [50]	Fluent	Building/turbine	2D	-	Realizable k-ε	Transient	Sliding mesh
Soebiyan et al. [51]	Win Air	Building	3D	97.5	-	Steady	-
Cho et al. [52]	Fluent	Building	3D	64	Standard k–ε	Steady	-
Kim et al. [53]	SC/Tetra	Building	3D	555	Standard k–ε	Steady	-
Jafari et al. [54]	Fluent	Building/turbine	3D	-	SST 4eq k-ω	Steady	Multiple reference Frame
Li et al. [55]	CFX	Building/turbine	3D	-	Standard k–ε	Transient	Sliding mesh
Abu-Thuraia et al. [56]	STAR CCM+	Building/turbine	3D	30.48	Realizable k-ε	Transient	Sliding mesh
Jafari et al. [57]	Fluent	Building/turbine	3D	96	SST k-ω	Steady	Multiple reference Frame
Shiraz et al. [58]	Fluent	Building/turbine	3D	30 and 142	Realizable k-ε	Transient	Sliding mesh

As seen in **Error! Reference source not found.**, Fluent was the most used solver in the primary studies (50%). On the other hand, Guerri et al. [46] implemented their own CFD code. All authors used Reynolds-Averaged Navier Stokes (RANS) equations for their simulations due to its relatively lower computational cost compared to both Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS). Note that numerical results of LES and DNS approaches depict better agreement with wind measurements around single buildings than the RANS approach, as shown in [62].

Most authors modelled both building (single building or urban environment) and UWT in a 2D or 3D dimensional domain (58%). Note that a precise description of the actual urban environment can be ensured only by 3D simulations of specific places [34]. Also note that 3D wind fields play the main role in the analysis of wind energy within urban environments [63]. According to the literature analysed, UWTs were mainly placed on a building roof to take advantage of the wind velocity amplification phenomenon, since wind velocity can be increased because of the shape of the buildings [52]. Note that an integrated building-turbine design is essential [41]. On the other hand, Zhu et al. [50] placed the wind turbine between two buildings to exploit the wind velocity amplification there.

Standard k–ε turbulence model was the most used within the primary studies (42%). y+ was considered according to the turbulence model requirements. Generally, boundaries conditions were set as velocity inlet, pressure outlet, symmetry, and wall. Steady-state was the most used instead of transient. In some studies, time steps information was not presented, so it could be difficult to reproduce numerical results found in the primary studies. Note that only Zhu et al. [50] and Colley [45] mentioned the computational time that they required for their CFD simulations, 40 h, and 8 - 10 h, respectively.

Additionally, computational domain and mesh features of the primary studies were depicted in **Error! Reference source not found.**.

Kim et al. [53] modelled an urban environment containing a 555 m. building height, so they constructed a large 3D domain, which contained 90 million unstructured mesh elements. Similarly, other studies containing a large number of mesh elements modelling a full urban environment.

Otherwise, it was common to see a mesh convergence study in each work. Note that the purpose of the mesh convergence study is to confirm that the refinement of the mesh does not affect the numerical results significantly [40].

The rectangular domain shape (hexagonal in 3D) was the most used (88%) due to its ease of construction. Unstructured meshes were preferred to model the UWTs. Note that an unstructured mesh is easier to build compared to a structured mesh, but the unstructured mesh is less accurate than the structured one.

3.4. RQ 3: Main Variables

The main variables identified in the primary studies are shown in **Error! Reference source not found.**.

Table 4. Computational domain and mesh features.

Author	2D/3D	Domain shape	Mesh type	Max. number of elements
Balduzzi et al. [34]	2D	Rectangular	Structured	80 000
Chong et al. [35]	2D	Rectangular	Structured	209 554
Heath et al. [36]	3D	Rectangular	Unstructured	-
Balduzzi et al. [38]	2D	Rectangular	Structured	80 000
Park et al. [39]	2D	Rectangular	Structured	-
Larin et al. [40]	2D/3D	Rectangular	Unstructured	5 000 000
Krishnan and Paraschivoiu [41]	3D	Rectangular	Unstructured	6 800 000
Dilimulati et al. [42]	3D	Octagonal	Unstructured	2 700 000
Bianchi et al. [43]	2D	Rectangular	Structured	80 000
Arteaga-López et al. [44]	3D	Rectangular	Structured	176 260
Colley [45]	2D/3D	Rectangular	Structured / unstructured	3 200 000
Guerri et al. [46]	3D	Rectangular	Structured	1 320 000
Hang et al. [47]	2D	Rectangular	Structured	152 326
Hassanli et al. [48]	3D	Rectangular	Structured	7 000 000
Riva [49]	3D	Rectangular	Structured / unstructured	1 000 000
Zhu et al. [50]	2D	C-type	Structured / unstructured	421 092
Soebiyan et al. [51]	3D	Rectangular	Structured / unstructured	-
Cho et al. [52]	3D	Rectangular	-	-
Kim et al. [53]	3D	Rectangular	Unstructured	90 000 000
Jafari et al. [54]	3D	Rectangular	Structured / unstructured	4 078 320
Li et al. [55]	3D	Rectangular	Unstructured	780 000
Abu-Thuraia et al. [56]	3D	Rectangular	Unstructured	10 850 000
Jafari et al. [57]	3D	Rectangular	Structured / unstructured	5 128 740
Shiraz et al. [58]	3D	Octagonal	Unstructured	33 000 000

Most authors used VAWTs as Darrieus and Savonius to calculate the main variables identified in this study, Af, Cp, and Ct. Energy output (compute in [36], [44], [51], [53]) was not considered in **Error! Reference source not found.** because it is a variable that depends on the rated power output of the UWTs (i.e., wind turbines sizes), thus, the energy output does not offer a reliable way to compare different findings.

Note that the self-starting capability and independence relative to wind direction make VAWTs attractive in urban environments [40].

Table 5. Main variables analysed.

Author	Wind turbine type	Wind turbine name	Amplif. system	Maximum coefficient
Balduzzi et al. [34]	VAWT	H-Darrieus	No	$A_f = 1.06$
Chong et al. [35]	VAWT	H-Darrieus	Yes	$C_t = 0.4195$
Heath et al. [36]	HAWT	Swift	No	-
Balduzzi et al. [38]	HAWT / VAWT	Darrieus	No	$A_f = 1.06$
Park et al. [39]	VAWT	Savonius, GWE-200BI	Yes	$C_p = 0.381$
Larin et al. [40]	VAWT	Savonius	No	$C_p = 0.24$
Krishnan and Paraschivoiu [41]	VAWT	Savonius	Yes	$C_p = 0.34$
Dilimulati et al. [42]	VAWT	Darrieus	Yes	$A_f = 1.6$
Bianchi et al. [43]	HAWT	-	No	$A_f = 1.06$
Arteaga-López et al. [44]	HAWT	Bergey Excel	No	-
Colley [45]	VAWT	Savonius	Yes	$C_p = 0.24$
Guerri et al.	VAWT	Darrieus	No	$A_f = 1.156$

[46]				
Hang et al. [47]	VAWT	Darrieus	Yes	$A_f = 1.63$ $C_p = 0.4627$ $C_t = 0.1851$
Hassanli et al. [48]	HAWT	Ampair	Yes (building)	$A_f = 1.8$
Riva [49]	VAWT	UNH-RVAT	No	$C_p = 0.246$
Zhu et al. [50]	VAWT	Darrieus	Yes (buildings)	$A_f = 1.68$ $C_t = 0.7833$
Soebiyan et al. [51]	HAWT / VAWT	AirForce 10, Power works 100, Sky stream 3.7, Aeolos v 3kw, UGE-9M	No	-
Cho et al. [52]	HAWT / VAWT	-	Yes (building)	$A_f = 1.4$
Kim et al. [53]	VAWT / HAWT	GWE-10KH / Excel-S	No	-
Jafari et al. [54]	LCWT	PowerWindow	Yes (building)	$C_p = 0.16$
Li et al. [55]	VAWT	Senegal type	No	$C_p = 0.134$
Abu-Thuraia et al. [56]	VAWT	Savonius	Yes	$C_p = 0.336$
Jafari et al. [57]	LCWT / HAWT	PowerWindow / Ampair	Yes (building)	$C_p = 0.16$
Shiraz et al. [58]	VAWT	Troposkein	No	$C_p = 0.4$

The conventional HAWTs that offer a relatively more proven technology do not outperform VAWTs in urban applications due to the high turbulent levels found in this type of environment [42], i.e. VAWTs operating in urban environments have a better performance than HAWTs. These high turbulent levels can make it difficult to catch a good quality wind flow [64] that could benefit HAWTs. Additionally, VAWTs show lowers vibration and noise levels compared to HAWTs [52]. VAWTs do not require yawing systems since they are less sensitive to wind direction changes [65]. On the other hand, some authors used amplification systems as shrouds or the designed buildings to amplify the local wind velocity. Particularly, power augmentation systems using diffusers and shrouded brims integrated with conventional wind turbines promise significant Cp increase [42].

The maximum Af of 1.8 corresponded to Hassanli et al. [48] who evaluated the performance of a Double Skin Façade (DSF) system used to generate energy throughout the Ampair wind turbines located within the system. Note that a drawback of this system is the occupation of a specific area within a floor in the building.

Regarding Cp, Hang et al. [47] recorded the higher one 0.4627 using an eco-roof system as an amplification device and a Darrieus wind turbine. Meanwhile, Chong et al. [35] obtained the highest Ct of 0.4195 using an H-Darrieus and a novel Omni-Direction-Guide-Vane (ODGV) as amplification system. Note that the maximum theoretical Cp of a Troposkein Darrieus wind turbine without an amplification device is 0.4 as shown in [66]. Also note that Darrieus wind turbines are considered as one of the most attractive solutions due to their low visual impact, reduced acoustic emissions, and better response to both turbulent and skewed incoming flows [34].

3.5. RQ 4: Research Tendencies

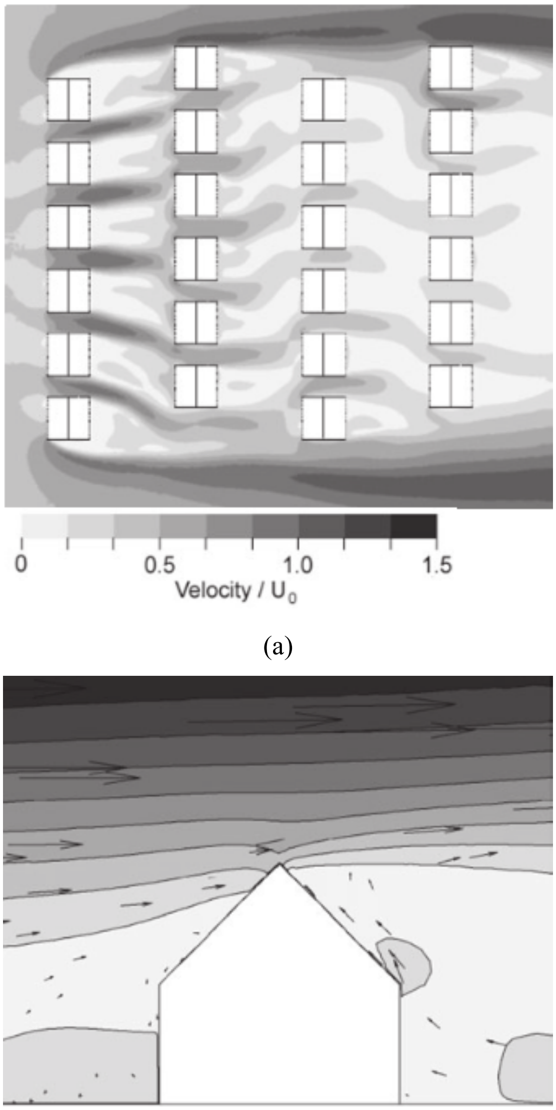
In this section, two research tendencies were evaluated, Building Mounted Wind Turbines (BMWTs) and Building Integrated Wind Turbines (BIWTs). BMWTs refer to wind turbines joined to the building structure where it functions as a tower to install the turbines [44]. Wind turbines installed in buildings that were designed with wind turbines in mind, i.e. buildings that were planned with the use of wind turbines in the blueprints of the buildings are known as BIWTs [44]. Note that building augmented wind turbines are included within BIWTs here.

3.5.1. Building Mounted Wind Turbines

One of the first CFD design works corresponded to Heath et al. [36] who proposed a methodology for estimating the energy production of a BMWT from simple information as to wind atlas wind speed and building density features. They analysed the wind flow behaviour around 24 houses as seen in **Error! Reference source not found.**a. For all locations, the numerical results showed variation in power output with change in wind direction, as seen in **Error! Reference source not found.**b.

Aerodynamic performance of a roof mounted VAWT, i.e., a BMWT were evaluated by Guerri et al. [46] using a CFD code and a program based on the BEM theory. The Cp values of the BMWT were higher than a rurally located wind turbine showing relations Cp,max/Cp,rural from 1.36 to 1.57.

More recently, Riva [49] evaluated the impact of the surroundings on the turbine performance installed on a building roof. **Error! Reference source not found.** shows the velocity streamlines around both the wind turbine and buildings studied. Three locations for the wind turbine were tested. Position 2 presented almost the same wind speed (9.95 m/s) that Position 1 (9.75 m/s, Cp = 0.23), but a lower efficiency (Cp = 0.17) that brought to a reduction in power production of 22%. Position 3 had a low wind speed (6.35 m/s, Cp = 0.13) due to the wind hit surroundings before flowing on the roof. As seen in **Error! Reference source not found.** and **Error! Reference source not found.**, as the wind flow approaches the buildings, the flow skews and accelerates over the building roof. This is expected as the presence of obstacles causes two effects, an acceleration of the wind velocity around the buildings and an increase in turbulence intensity [67].



(a)

(b)

Fig. 4. Normalized magnitude of the wind speed: (a) plan view at the middle height of the houses array and (b) elevation view of a house [36].

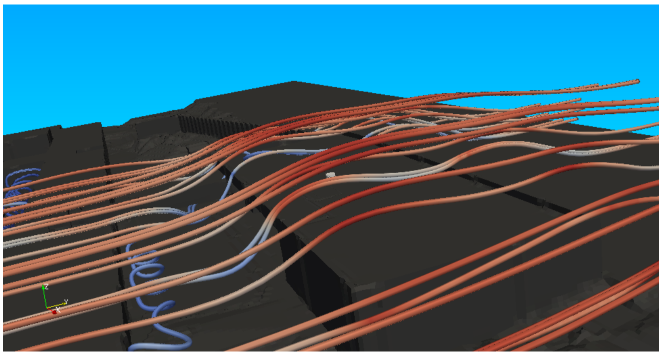


Fig. 5. Velocity streamlines around both the wind turbine and buildings [49].

Taking into account the wind resource assessment of 2D urban environments, Balduzzi et al. [38] performed a parametrical CFD analysis of the wind behaviour on a building roof located in an urban environment to evaluate the viability of UWTs installation. The CFD analysis was carried out characterizing the wind behaviour in a zone 2 m above the building roof corner as a function of the installation building height (H), the height (h) and width of its upwind building, and the distance between the buildings themselves (D). The analysis also considered the presence of either a flat or a sloping roof. The results showed that the skew airflow had a negative effect on the energy production of HAWTs. Conversely, VAWTs provided interesting perspectives, since they took advantage of the skewed airflow condition to improve their lower efficiency.

Additionally, to estimate the impact of the skewed airflow (i.e., incoming flow inclination, γ) on the performance of HAWTs, a simulation code based on the BEM approach was developed and validated by Bianchi et al. [43]. See urban configuration and location of parameters studied in **Error! Reference source not found.**. In the case of a low inclination angle, a reduction of up to 4% of the wind energy potential was calculated. On the other hand, higher inclination angles reduced the wind energy potential by about 9%. Note that to measure wind velocities above a sloping building roof, CFD approaches could be more appropriate than manual measurements [68].

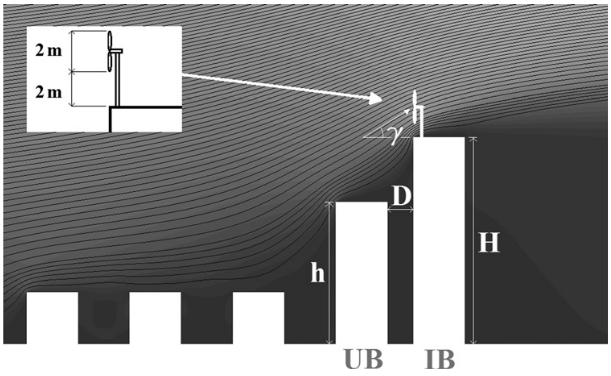


Fig. 6. Investigated configuration used in [43].

Balduzzi et al. [34] also developed a numerical model based on CFD to consider the effects of skewed airflow on the performance of a Darrieus VAWT installed on a building roof in a reference European city. The authors also evaluated the behaviour of the Darrieus VAWT using the CFD model developed. The results showed a power increase of up to 6% of the VAWT in skewed conditions. The authors concluded that this improvement could also lead to a reduction of the minimum cut-in speed extending the operating range of the VAWT and increasing the energy production for low wind conditions.

A wind resource assessment procedure for BMWTs, which combines remote sensing, numerical weather prediction, and CFD, was proposed by Kim et al. [53]. The Lotte World Tower was used as a case study. Details of the tower are shown in **Error! Reference source not found.**a. Comparisons of CFD results (both wind speed and turbulence intensity) and LIDAR measurements showed good agreement when the Lotte World Tower was not simulated. The CFD results, when the Lotte World Tower was simulated, showed that the tower roof was negatively affected by surrounding buildings reducing the wind speed there by about 3%, as noted in **Error! Reference source not found.**b. The authors determined that a capacity factor of 6.4% could be reached by the BMWT simulated.

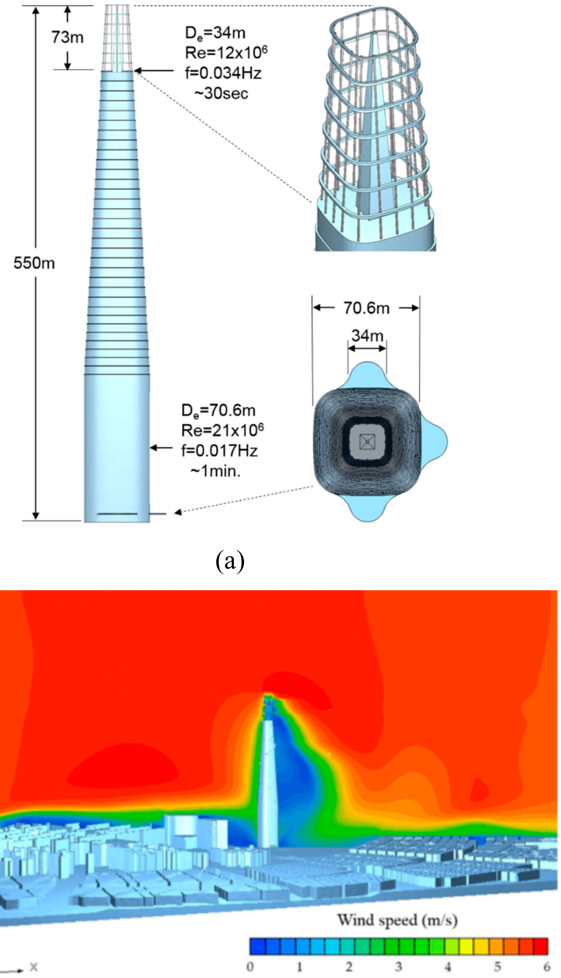
Soebiyan et al. [51] determined the wind energy potential of high-rise buildings, which were located in a humid tropical climate, regarding wind velocities and directions depending on seasons. The highest energy production was obtained from a 100 kW HAWT at 5.2 m/s average wind speed.

Li et al. [55] investigated a Senegal VAWT under different configurations to find an optimal design that would have low cut-in speed, high energy density, and robustness. Thus, a 2 kW prototype system was developed based on the VAWT design and located at a building roof. Velocity vectors around the VAWT are shown in **Error! Reference source not found.**. The results showed that an obstacle located in front of the VAWT can influence the airflow field passing through the VAWT and reducing thus the energy production of the turbine. A numerical and experimental study of an orthopter VAWT, which is suitable for power generation in urban environments, can be found in [69].

On the other hand, Hang et al. [47] performed an analysis and optimization of a V-shape accessorial roof to maximize the performance of a VAWT installed in the accessorial. The optimization consisted of varying pitch angles of the accessorial to determine the best VAWT performance through numerical simulations. Pitch angles between -45º and 60º were used during the simulations. Additionally, an experimental model was developed to verify the wind amplification effect of the V-shape accessorial roof. The accessorial V-shape roof with a pitch angle of 19.5º showed the best wind velocity amplification effect (63% velocity increased) in the central vertical region of the accessorial. Additionally, similar studies analysing wind flow through accessorial roofs can be found in [70] and [71].

Regarding amplification devices for UWTs installed on buildings roofs, Chong et al. [35] designed a novel ODGV, which surrounds a VAWT, to improve the performance of the turbine. Details of the apparatus set-up are shown in **Error! Reference source not found.**. First, some experiments were performed for two configurations, a bare VAWT installed on a simulated building roof and the ODGV integrated with the VAWT. Then, the ODGV integrated with the VAWT was verified by CFD simulations. At TSR = 5.1, the average Ct of bare VAWT was 0.3681, but the average Ct of the ODGV integrated with the VAWT was 0.4195, which is equivalent to a 38.6% increase. Another numerical and experimental study including an amplification device also called wind booster can be found in [72].

Similarly, Colley [45] evaluated the performance of a novel crossflow for wind turbines. This device uses an outer stator guide vane to improve the energy production of the turbines. The effects associated with the installation of the wind turbines in the urban environment were also studied. A Cp of 0.24 was obtained by the author at 12 m/s wind velocity. The results also showed that the maximum energy generation on flat roof geometries was achieved for a wind turbine located on the upstream side of the building roof obtaining a Cp of 0.35, which represented a 71% wind velocity increased.



(a)

(b)

Fig. 7. Lotte World Tower: (a) dimensions and (b) velocity contours around it [53].

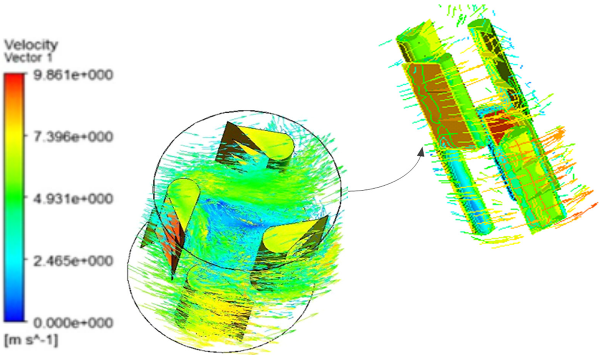
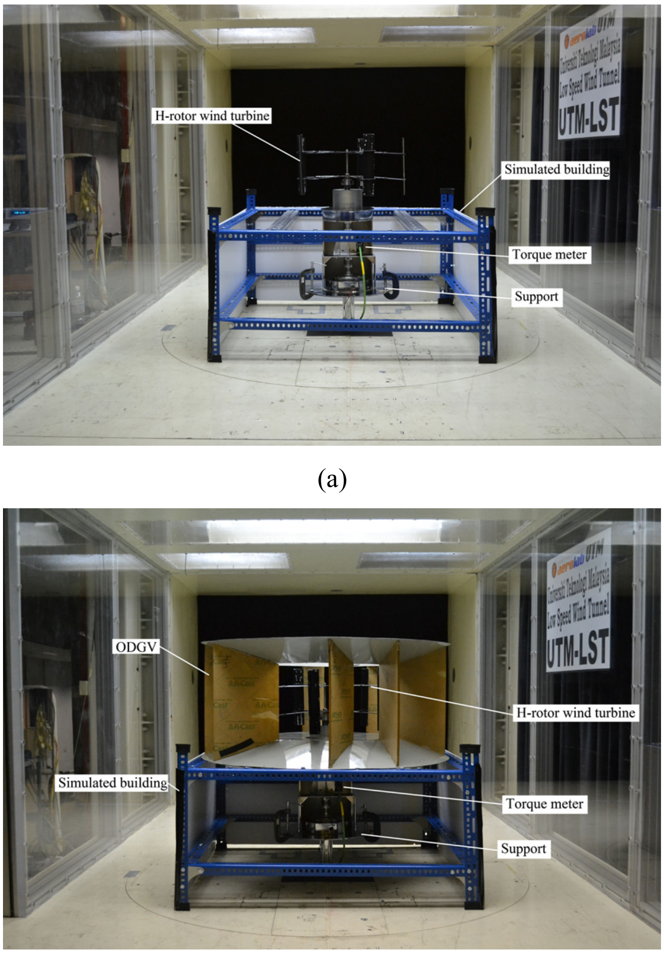


Fig. 8. Velocity vectors of the proposed wind turbine [55].



(a)

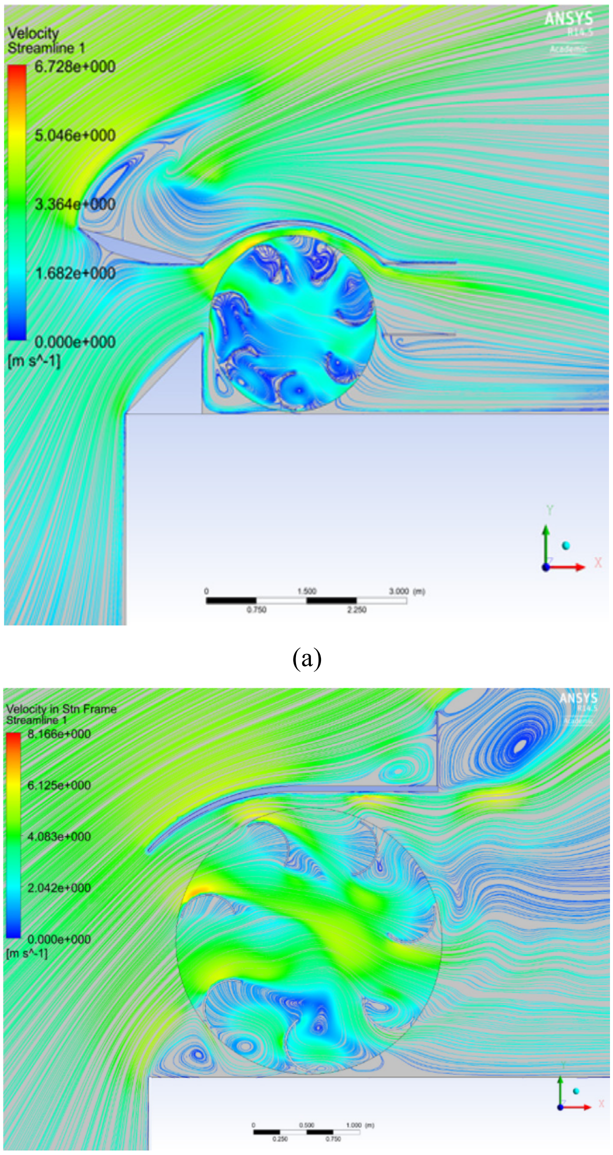
(b)

Fig. 9. Apparatus set-up for a H-rotor wind turbine (a) without ODGV and (b) with ODGV [35].

Krishnan and Paraschivoiu [41] carried out a study to increase the performance of a Savonius VAWT integrated with a diffuser-shaped shroud (i.e., initial design), which was installed on a building roof. Three shape modifications as the incorporation of a flange at the end of the shroud, the elimination of the front door, and some cuts at the end of the VAWT blades were performed in the study. The Cp of the final design was improved from 0.135 to 0.34. The velocity streamlines through the initial and final designs are depicted in **Error! Reference source not found.**.

Similarly, a horizontal configuration of a Savonius VAWT was proposed to be located on the upstream side of a building by Larin et al. [40]. Parameters as position, blade number, and a circumferential length of the VAWT were investigated by the authors. The optimal configuration showed an increase in Cp from 0.043 to 0.24, i.e. an improvement of 450%.

Moreover, Abu-Thuraia et al. [56] studied the performance of a seven-bladed Savonius VAWT which was horizontally oriented. This turbine was integrated inside a diffuser-shaped shroud. Some guide vanes were placed forward the diffuser shroud to improve the VAWT performance.



(a)

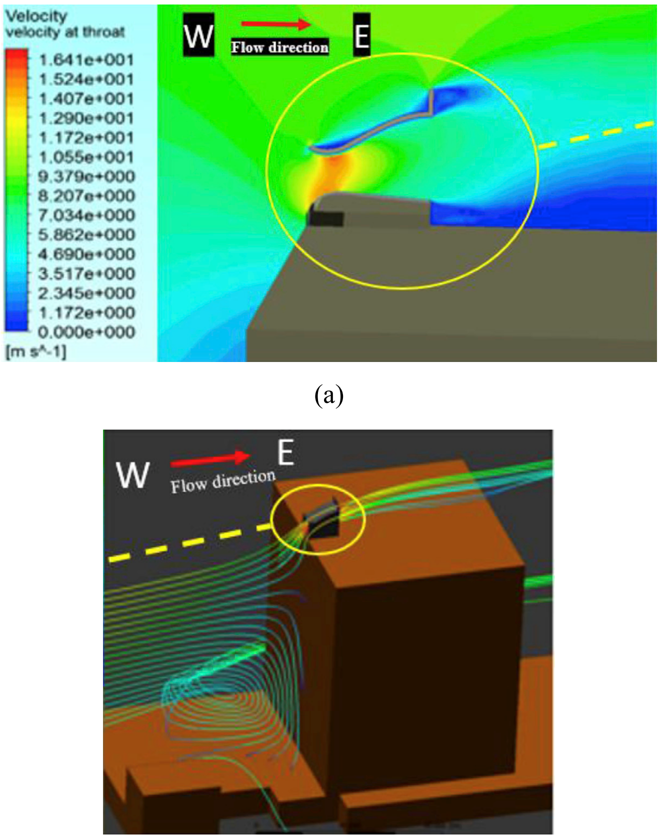
(b)

Fig. 10. Velocity streamlines over (a) the initial design and (b) the final design [41].

Note that this wind turbine was studied in the past [40], [41]. The analyses of the guide vanes indicated a maximum Cp of 0.33 at vanes angle of 55°. Note this Cp value was lower than one obtained with the case without guide vanes (Cp = 0.394).

Besides those studies, Dilimulati et al. [42] studied a flanged diffuser shroud device, which could be integrated with a VAWT horizontally oriented. The authors placed the device on a building roof via CFD simulations to improve the VAWT performance. Velocity contours and velocity streamlines are shown in **Error! Reference source not found.**. Two urban areas, a Low Building Density (LBD) and a High Building Density (HBD), were simulated. Eight different wind directions were taken into account in the study. The results showed that the wind velocity could accelerate up to 1.6 times the upstream velocity at the throat of the diffuser.

On the other hand, Arteaga-López et al. [44] proposed a methodology that permits the application of diverse CFD methods and software to assess the installation of UWTs. **Error! Reference source not found.** shows the process flow diagram of the methodology proposed and the velocity streamlines around five Bergey Excel 10 kW wind turbines installed on a building roof. Additionally, the methodology could reduce the time and cost of the feasibility studies of wind projects for designers and planners.



(a)

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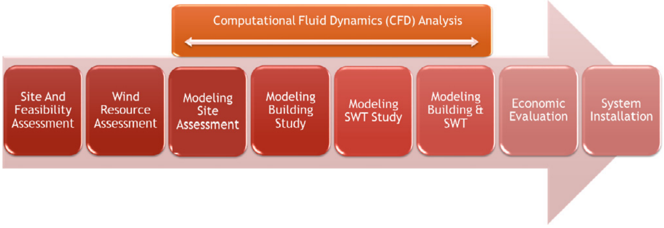
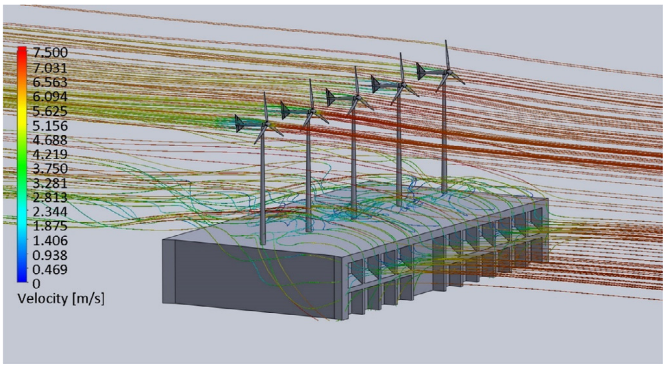
Fig. 11. Flanged diffuser shroud mechanism on the roof of a building: (a) velocity contours at symmetry plane and (b) velocity streamlines in perspective view [42].



(a)

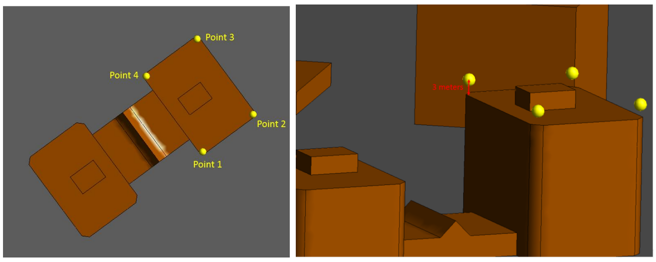


(b)

Fig. 12. Methodology proposed in [44]: (a) process flow diagram and (b) velocity streamlines around five Bergey Excel 10 kW wind turbines installed on a building roof.

More recently, Shiraz et al. [58] also proposed a methodology to evaluate the performance and energy output of BMWTs. The methodology combined CFD and meteorological data. Two urban areas were simulated LBD and HBD. HBD was part of downtown and LBD was a commercial area in a suburban region (Montreal, Canada). Eight different wind directions were simulated as in [42] to calculate the wind velocity at four control points representing the placement of UWTs at the corners of two buildings. The location of the control points is shown in **Error! Reference source not found.**. The authors concluded that the methodology presented could be used to simultaneously analyse places and turbines located in urban environments.

To summarise, the design and evaluation of BMWTs have evolved from 2D to 3D analyses incorporating more detail into UWTs and urban environments modelling. This tendency points out to improve the fidelity of wind behaviour in urban environments. The UWT power output evaluation has passed from the use of the power curve of commercial UWTs to the determination of the power output via full 3D CFD, which is possible to thank the developments in computational power. On the other hand, in the last years, some novel UWTs and wind amplification devices have been developed to increase the wind turbines' performance achieving promising results. Additionally, design methodologies have been proposed to improve the design process and analysis of the UWTs installation.



(a)

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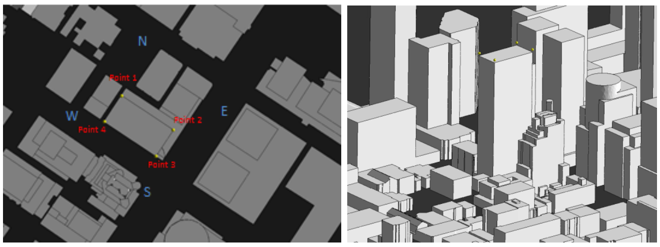


(c) (d)

Fig. 13. Control points location: (a) top view for LBD, (b) isometric view for LBD, (c) top view for HBD and (d) isometric view for HBD [58].

3.5.2. *Building Integrated Wind Turbines*

Cho et al. [52] proposed BIWTs based on the analyses of maximum wind velocity which passes through an area located on five building types (A, B, C, D, and E). The results showed that the wind velocity could be augmented through building design to maximize energy production using specific wind turbines. The authors recommended specific wind turbines depending on building types: A (HAWT), B (HAWT), C (VAWT), D (VAWT), and E (VAWT).

Zhu et al. [50] investigated a Building Augmented three Straight-Bladed Vertical Axis Wind Turbine (BASB-VAWT) to improve its operational parameters. Note that this type of wind turbine refers to BIWTs. The results showed that parameters as wind direction, aerofoil types, σ, and architectural configurations had an important influence on the performance of the BASB-VAWT.

On the other hand, Park et al. [39] proposed a novel BIWT system. This BIWT directly used the building walls for its installation. The proposed system combined guide vanes and Savonius VAWTs as seen in **Error! Reference source not found.**. Through CFD simulations, the optimal configuration of the system and its associated energy production was determined. One module (i.e., a guide vane and a Savonius VAWT) could produce 0.248 kWh/day on average, and 0.410 kWh/day in spring. Note that one module had an inlet area of one square meter. The total energy produced from the whole system (several modules) was estimated at 241 kWh/day.

Recently, a methodology that uses CFD simulations was developed by Hassanli et al. [48] to evaluate the performance of a DSF system. This system had openings and corridors used to guide the wind towards Ampair HAWTs, which were installed within the corridors of buildings. More details are shown in **Error! Reference source not found.**, generating an amplification effect in the wind velocity and wind turbines power output, as seen in **Error! Reference source not found.**. The results showed that an amplification up to 1.8 times was achieved in the wind velocity within the corridors. The authors also concluded that the wind turbines installed within the system (urban environments) could generate up to 50% additional energy compared to wind turbines located in regions with free stream conditions (isolated regions).

Otherwise, Jafari et al. [54] studied two configurations (elevated and ducted) of a wind turbine called PowerWindow using CFD. The results showed that Cp of 12% and 8% were calculated for the ducted and elevated configurations, respectively. The authors also found that an increment of σ led to both a reduction of the maximum lift coefficient and an increment in the angle of attack needed to reach stall. Note that studies, where VAWTs placed in confined long channels, were also carried out as seen in [73].

Similarly, Jafari et al. [57] studied both stator augmented PowerWindows and Ampair 300 HAWTs when installed within building openings. Detail of location of both turbines is depicted in **Error! Reference source not found.**. Meshing details are also showed in **Error! Reference source not found.**. The authors used an approach called the equivalent momentum sink method along with CFD simulations to predict the wind features as pressure, velocity, and turbulence intensity within the ducts. The results showed that the turbines installed within building openings could improve their performance compared to wind turbines under free stream conditions. The authors also found that the energy production of the PowerWindow did not increase as much as the Ampair 300 HAWT.

It is important to note that 3D simulations of wind flow through urban environments are more reliable than 2D simulations due to the former presents more realistic information about the wind behaviour that takes place in these particular environments. For instance, as seen in **Error! Reference source not found.**, the wind flow through the 2D environment does not take into account the wind behaviour at the corners of the building, which can change the content of energy incorporated in the wind. Moreover, the 2D simulation does not show the reattachment of the flow behind the high-rise building, which is showed in 3D simulations and confirmed by experimental results as seen in [74].

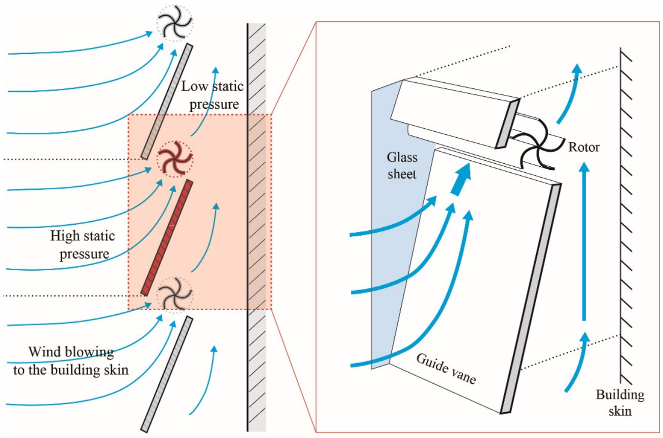
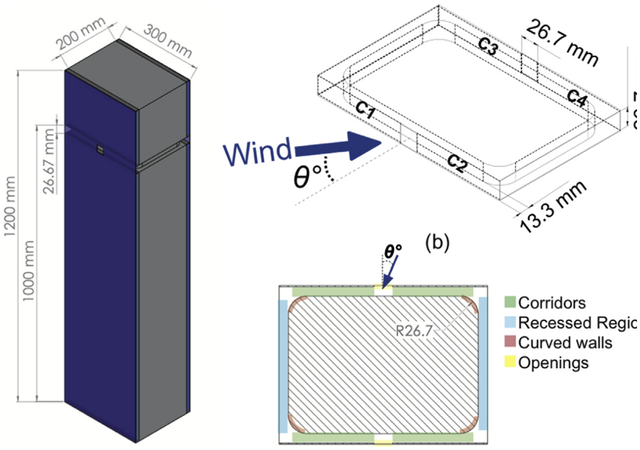


Fig. 14. Illustrative view of the innovative building-integrated wind turbine proposed in [39].



(a) (b) (c)

Fig. 15. Detail of the special Double Skin Façade system used in [48].

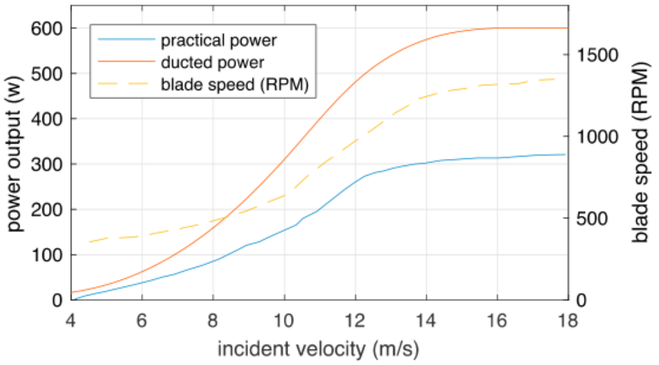
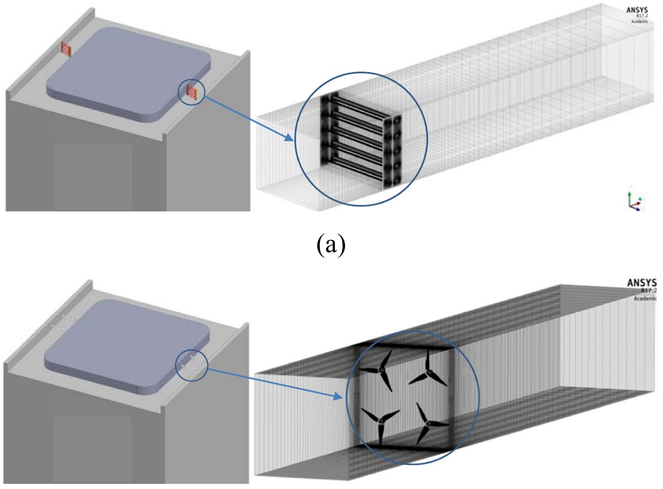


Fig. 16. Power output and RPM of Ampair 300 in free-stream and inside a duct [48].



(a)

(b)

Fig. 17. Ducts containing (a) the LCWT system and (b) the HAWTs [57].

On the other hand, 2D approaches only permit the simulation of the wind flow in one direction, which made it impossible to calculate the energy produced by BMWTs for all directions from where the wind blows. It is also known that 3D simulations of wind turbines can predict in better agreement the interactions and power produced in comparison to 1D or 2D approaches, which tend to overestimate the power for low tip speeds [75].

To sum up, all simulations regarding BIWTs modelled only the objective buildings where UWTs were installed. These simulations were based on 2D or 3D incorporating detail of UWTs and buildings. The UWT power output evaluation was mainly by means of determining the power output via full 2D or 3D CFD. Similar to the BMWTs studies, some novel UWTs, wind amplification devices, and systems have been developed to increase wind turbine performance.

4. Future Works

Detailed wind field measurements of an area within a city, which is important to validate numerical models in the validation stage, are needed. It is also necessary to measure the performance of UWTs installed in cities.

It is also important to know the computational cost of CFD simulations represented by CPU time and number of elements (which could give us an insight into the required RAM memory needed to solve a specific problem), in this sense, future research needs to show these parameters in their analyses. Additionally, simulations of both wind turbines and urban environments using LES and DNS approaches are required to improve the fidelity of wind behaviour and UWT performance within urban environments.

It is necessary to develop more integrated design approaches for the CFD design of UWTs. Fields included in these approaches could be blades' aerodynamics and materials (structural analysis), vibration, stability control, economic and environmental analysis (visual, noise, and biodiversity analyses).

On the other hand, analysing the impact of incorporating wind turbines into a distribution electrical system (conventional or smart grid), when different wind conditions (i.e., wind velocities and directions) happened throughout a period, would also represent a future work.

Since reviewed scientific literature depicts the simulation of just one turbine per case, it would be interesting to study the wind behaviour throughout several UWTs located in urban environments and their interactions when the turbines and buildings create wind shadows behind them, which reduce the performance of the UWTs downstream. The development of control methods to reduce the effect of wind shadow on wind turbine performance would be also future work.

Development and optimization of novel wind turbines and amplification devices to improve the performance and reliability of the turbines represent a future work. In this case, wind turbines, amplification devices and the urban environment have to be simulated together.

Stochastic modelling and optimization of urban wind turbines under scenarios including buildings height modification in the urban environment, and wind turbine blades materials wear respect to different weather forecast also represent future works.

5. Conclusions

In this study, the development of a SLR to introduce recent advancements in the field of CFD design of UWTs was performed. To obtain suitable primary studies (papers and theses) to analyse and discuss in the SLR, four RQs were proposed. The answer to these RQs gave us an insight into the state-of-the-art and future trends in the field of CFD design of UWTs. Together with the SLR, critical analyses of the advancements in UWTs were carried out.

In all the primary studies, geometrical simplifications of 2D or 3D urban environments were performed which can affect the wind flow modelling since a precise description of the real urban environment can be ensured only by 3D simulations. UWTs using amplification systems were placed on buildings roofs to take advantage of the wind velocity amplification phenomenon and increase Cp since as the wind flow approaches the buildings, the flow skews and accelerates over the buildings' roofs.

Most authors used VAWTs as Darrieus and Savonius in their analyses. Note that the self-starting capability, lower vibration, lower noise levels, and independence relative to wind direction make VAWTs particularly attractive in urban environments. Also note that the maximum Af, Cp, and Ct found in the primary studies were 1.8, 0.4627, and 0.4195, respectively.

Within CFD configurations, the standard k–ε turbulence model was the most used (42% of the studies). y+ was considered according to the turbulence model requirements. The boundaries conditions were set as velocity inlet, pressure outlet, symmetry, and wall. Steady-state was the most used instead of transient. The rectangular domain shape was the most used (88%) while unstructured meshes were preferred to model the UWTs. RANS approach was used for all the simulations.

Simulation of BMWTs has evolved from 2D to 3D analyses incorporating more detail to UWTs and urban environments modelling. The BMWTs power output evaluation has passed from the use of the power curve of commercial UWTs to determine the power output via full 3D CFD. Meanwhile, the BIWTs power output evaluation was mainly by means of determining the power output via full 2D or 3D CFD. Both BMWTs and BIWTs related works developed some novel UWTs and wind amplification devices to increase the wind turbine performance achieving promising results. Additionally, design methodologies were proposed to improve the design process and analysis of the UWTs installation.

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