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ORIGINAL RESEARCH ARTICLE

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A Case Study for Small-Scale Vertical Wind Turbine Integrated Building Energy Saving Potential

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Abstract: Vertical Axis Wind Turbine (VAWT) is one type of wind machines, which is used nowadays to produce electricity. On the other hand, the VAWTs continue to evolve, driven by ongoing research, technological innovation, and the growing demand for clean and sustainable energy solutions. In terms of global sustainability, buildings prove to be major energy consumers. Even as technology advances to construct environmentally friendly buildings, various buildings are still contributors with high energy consumption. Novel systems are required to decrease energy consumption of today buildings. To this aim, this study offers an active solution by a renewable energy source in order to decrease energy consumption of an existing building. The novelty of the paper is designing three blades IceWind Turbine with arc angle of 112 degrees and an aspect ratio of 0.38 and integrating them to an existing building. A case building, occupied by a guard and used as a headquarters by soldiers on guard duty, in İstanbul Airport/Turkey is selected and 40 small-scale IceWind Turbines are integrated into the building via a dynamic building energy simulation tool and the results showed that total energy consumption of the case building is decreased by 9.3%. The outcome of this paper depicts that different design of the small-scale vertical wind turbines could be integrated to the building with higher energy saving potential.
Keywords: IceWind turbine; Building energy efficiency; Energy consumption; Building energy simulation; Integrated energy systems

1. Introduction

Energy consumption is deemed one of the most crucial issues that the world faces currently, and most countries utilize some form of integrated methods to enhance energy efficiency, particularly concerning energy consumption in buildings[1], as buildings constitute approximately 40% of the total energy consumption share. The most recent analysis of building energy utilization figures for Turkey[2] reveals that the distribution of usage of non-renewable energy and renewable energy consumption in buildings is 78% and 22%, respectively.

Natural energy assets are among the most vital sources that countries rely upon in their sustainable development. Today, developed countries have invested in their natural reservoirs; however, these nations have seamlessly integrated renewable and non-renewable energy effectively. Meeting energy needs grows challenging day by day, so that studies are now being regularly undertaken to find the most effective renewable energy technology[3]. A method utilized to decrease energy consumption of buildings is using wind energy, even PhotoVoltaic Panels are the most used technology, where small-scale wind turbines are implemented on the roofs of the buildings[4]. There are several types of small-scale wind turbines used on the top of buildings, including IceWind type due to its simple design. (**Figure 1**) shows schematic diagrams of small-scale vertical axis wind turbine installed on the rooftop of a building.

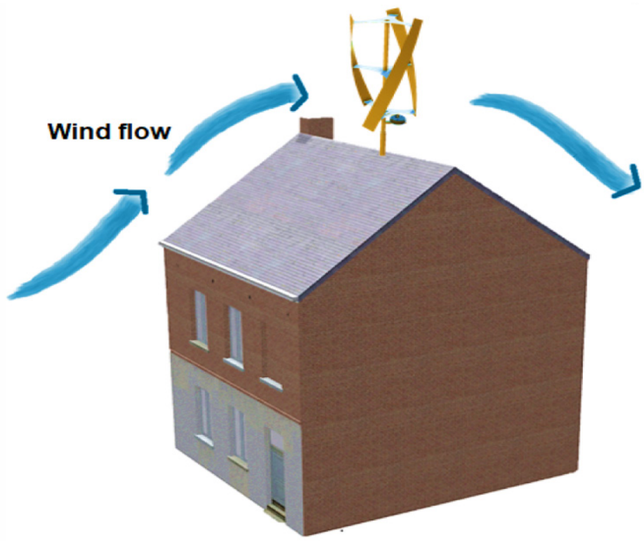


Figure 1. Small-scale vertical axis wind turbine mounted on the roof of a building[5]

There are limited studies which investigated the IceWind Turbine and its efficiency, for instance, Afify[6] found that the IceWind Turbine demonstrated similar efficiency with marginally higher values of rotational speed and static torque when compared with the Savonius Wind Turbine. The author also showed that performance of a two-blades IceWind Turbine showed a similar level of effectiveness and vortices compared to Savonious Wind Turbine. In another study by Mansour et al.[7], the IceWind Turbine were verified to be 3-times effective than Savonius Wind Turbines. According to Suffer and Jabar[8], increased number of IceWind blades increased turbine output power. However, there are very limited investigations which integrate small-scale wind turbines on the residential buildings. Mao et al.[9] investigated the edge-mounted Savonius turbine has a higher coefficient of power than the turbine working in consistent flows. It is also observed that the flow around the building has a substantial influence on turbine performance, particularly when the turbine is positioned downwind of the building.

On the other hand, Skvorc et al.[10], studied wind energy utilization on high urban buildings, taking into account factors such as local wind patterns and building design. The case study focused on the importance of suitable turbine selection and improved wind turbine efficiency in urban environments. Jooss et al.[11] conducted a study on the performance of a vertical axis wind turbine and flow field on building models to obtain the perfect position of the wind turbine and the results purposed the central position on a building is a good balance for effectiveness. On the other hand, Hirschl.[12] evaluated the performance of small-scale wind turbines on different roof shapes and the results showed that average speed was found as 0.2 m/s on gable roofs and 0.4 m/s on flat roofs at hub height (7m). Ibrahim et al.[13] investigated two types of vertical axis wind turbine (Savonius and Darrieus rotors) on the top of gabled roof shape and performance of the maximum power output increased from 1.4 watt to 2 watts when integrated on the building roof.

The novelty of this paper is to design 40 IceWind type vertical wind turbines and to integrate this novel design on the top of building to reduce energy consumption of a case building.

2. Methodology

(**Figure 2**) shows the flowchart of the study. A case building in İstanbul Airport/Turkey is selected for the application of wind turbines. As a first step, the building is modelled in a well-calibrated dynamic energy simulation tool. Then, the energy consumption of the baseline model, which consists of total energy such as electricity and fuel consumption minus any on-site electricity generation, is calculated. Afterwards, a novel design of wind turbines is integrated to the baseline model and re-simulated. The energy consumptions and energy saving potential of wind turbines are compared.

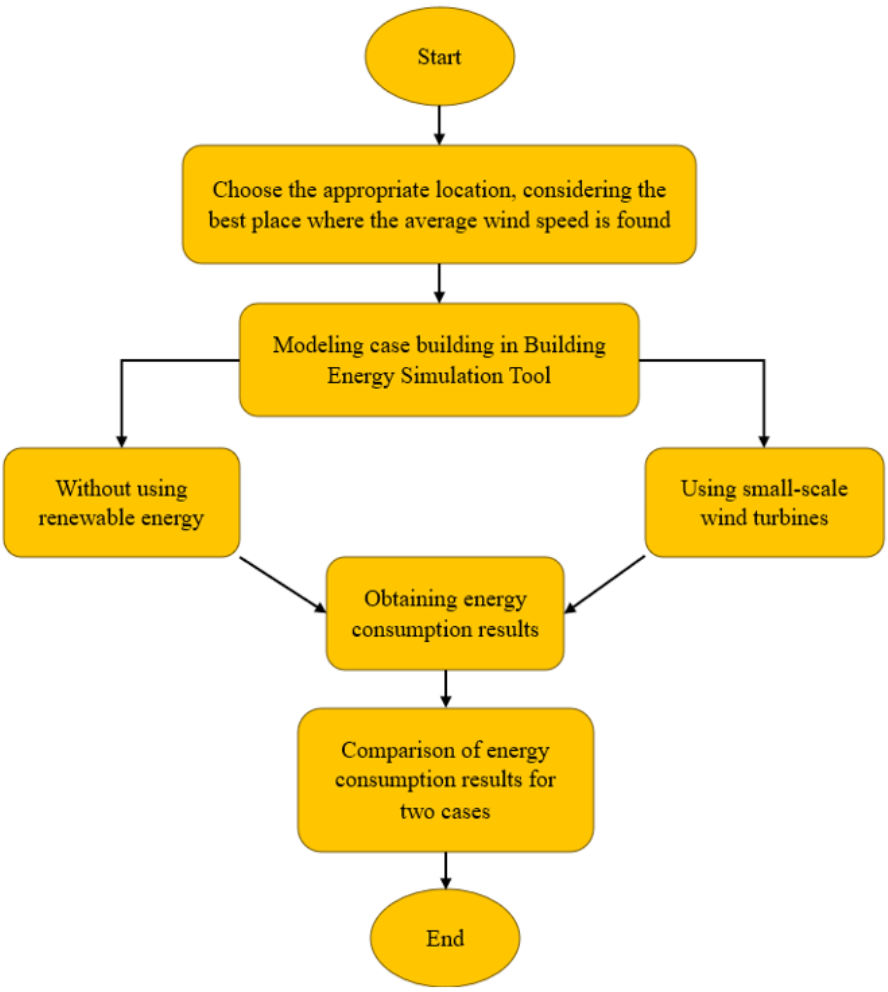


Figure 2. Flow chart of the study

2.1 Climate and Location Analysis

According to geographical maps, there are few regions which are appropriate for designing and constructing wind turbines in Turkey. For instance, the geographical map for the distribution of wind energy in Turkey, the annual wind speed in the Marmara district exceeds 4 m/s, however, in the middle of the Turkey, this value is decreasing to 2 m/s. To this aim, İstanbul /Turkey is selected among the best suitable regions in Turkey for wind energy generation[14]. The case building is chosen as a building in Istanbul, situated in the Northwest of Turkey (latitude 41° 00 N, longitude 29° 00 E), according to Köppen's climate classification, Istanbul has Csa type (temperature) climate zone[15], (**Figure 3**).

Figure 3. Location of Istanbul-Turkey

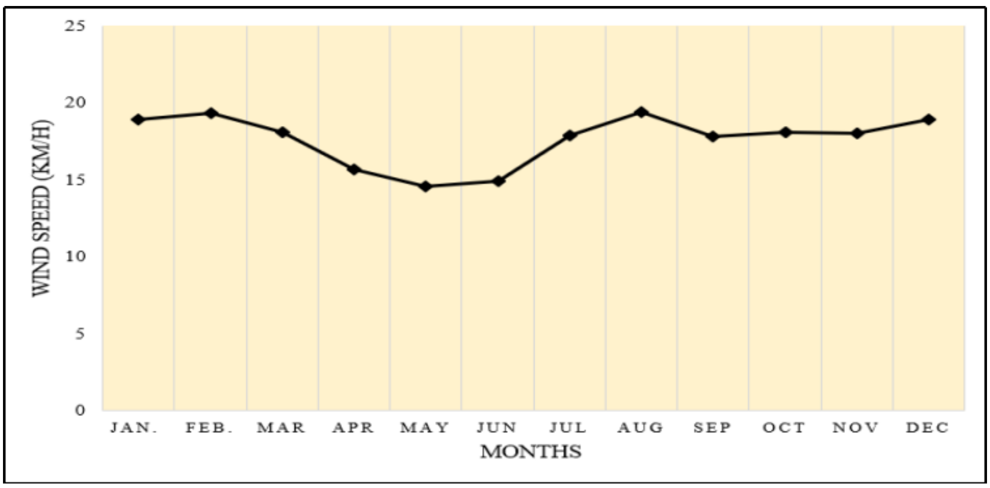


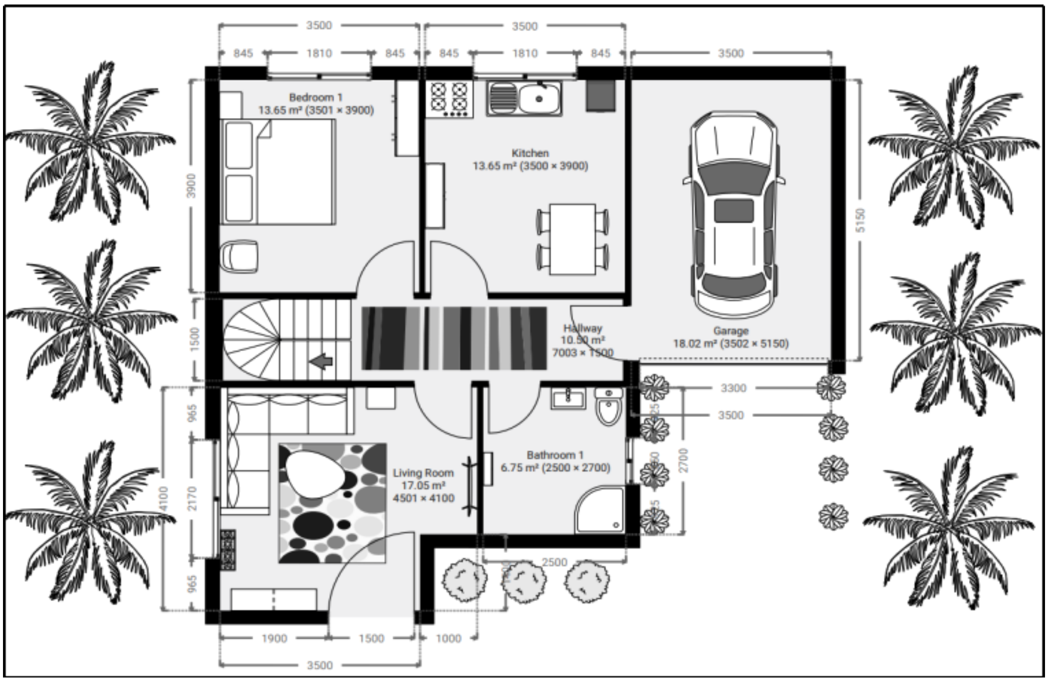
Figure 4. The values of wind speed for each month

(**Figure 4**) depicts the annual wind speed of the selected case area. The average wind speed is measured as 4.9 m/s. The figure depicts that wind speed values in case area vary throughout the year, influenced by seasonal changes and geographical factors. During the spring and summer months, the prevailing winds are typically lighter, with average speeds ranging from 15 to 18 kilometers per hour. Since the selected case area is near the coastal zones, august brings the strongest winds to the Istanbul, with gusts often reaching 20 kilometers per hour, particularly along the Bosporus strait and the city's exposed coastal regions.

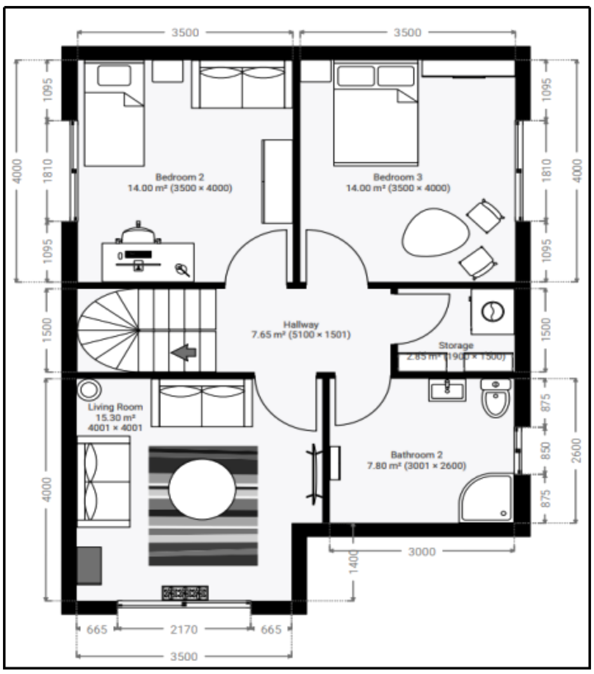
The monthly average of wind speed is lower in May compared to other months in the case area.

2.2 Case Building Design

The case building in İstanbul Airport/ Istanbul/ Turkey is investigated as a case study and baseline design of the building is shown in (**Figure 5**). The case building is used as a headquarters by soldiers on guard duty and is comprised of 2 floors: ground floor includes a bedroom, a living room, a kitchen, a hallway, a bathroom, and a garage for cars while first floor consists of two bedrooms, a family hall, a bathroom, a hallway and a storage room. The total area of the case building is 141 m^2.



(a) Ground Floor



(b) First Floor

Figure 5. Architectural drawings of the Residential plan

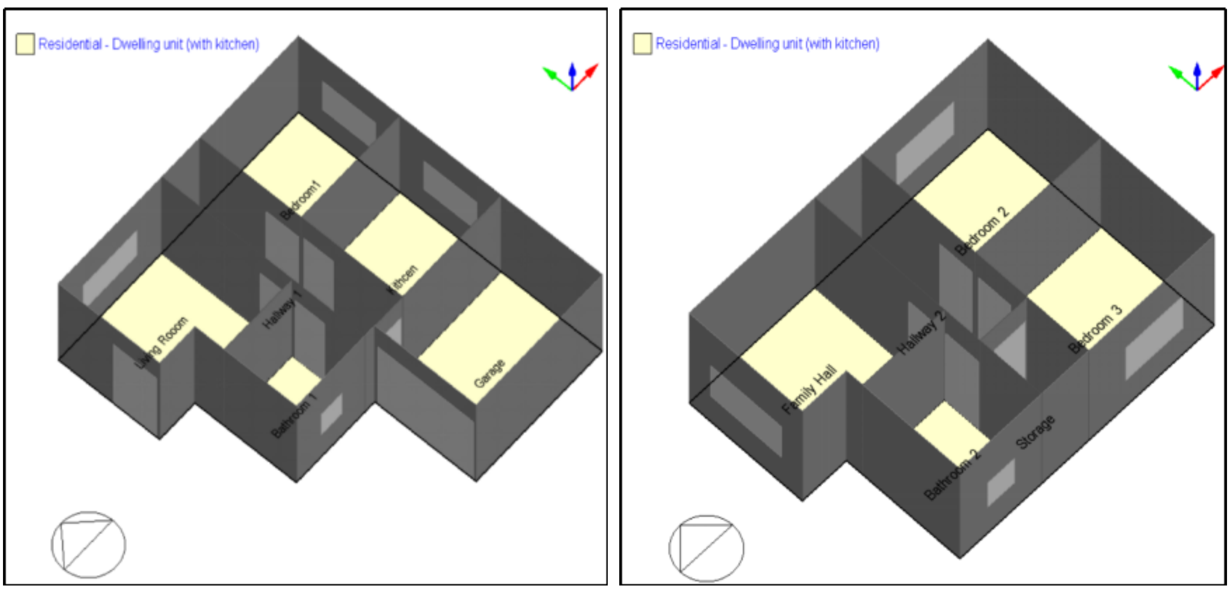
Case building parameters are taken from architectural drawing of the building. (**Table 1**) lists the design criteria and features of the case study building. According to Turkish Standard these sequence layers were taken from[16] for small residential building with a flat roof. The sequence layers of the external walls in the base design from outer surface to inner surface are Gypsum plastering with a thickness of 0.03m and thermal conductivity of 0.4 (W/mK), XPS Extruded Polystyrene with 0.07m and 0.034 (W/mK), Concrete Block with 0.1m thicknesses and 0.013 (W/mK) thermal conductivity, and Gypsum plastering 0.02 m thicknesses with 0.4 (W/mK) thermal conductivity. The U-value of the external walls is calculated as 0.335 (W/m^2K).

Table 1. Basic design features

The building construction properties	*Baseline model*
Number of floor	2
Overall floor area	141 m^2
Number of spaces	12
External walls (U-value)	0.335 (W/m^2 K)
Inernal walls (U-value)	1.923 (W/m^2 K)
Roof (U-value)	0.239 (W/m^2 K)
Ground floor (U-value)	0.423 (W/m^2 K)
Glazing type + U-value	Reference glazing with 1.978 (W/m^2 K)

2.3 Energy Simulation Analysis

For simulating energy consumption values, an hourly building simulation tool, called DesignBuilder, is selected[17]. As a first step, case building is modelled in the tool (**Figure 6**). The materials of the construction of case building are taken from architectural drawings and the model is constructed with the values of (**Table 1**).



(a) Ground Floor (b) First Floor

Figure 6. 3D shot of the basic design model

(**Figure 7**) shows baseline model as a three-dimensional modelling. Additionally, it is worth to note that the case building is modeled with surrounding trees to receive accurate results through the utilization of shading effects and simulated under the weather file of Istanbul/ Ataturk Airport. There are two cases used to simulate, first one without any active solution and other case with small-scale wind turbines on the rooftop of the case building.

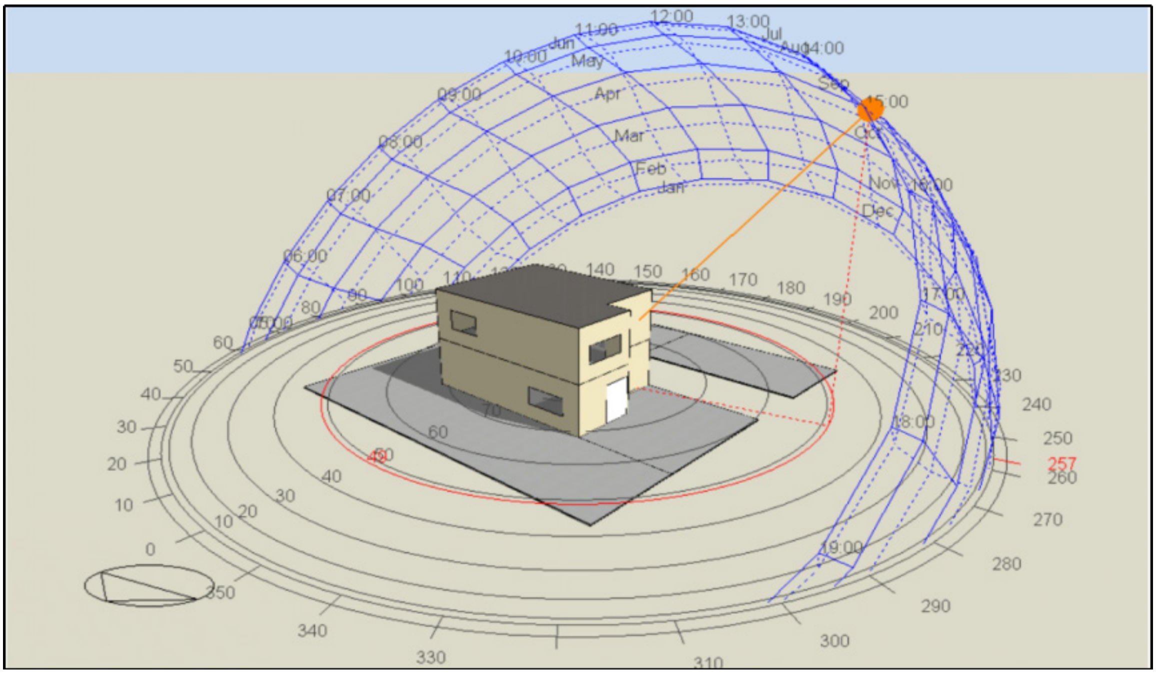


Figure 7. Building Energy Simulation Model of the Case Building

2.4 Building-Integrated Wind Turbine Design

Renewable energy could be considered as one of the most energy retrofitting strategy for residential building due to its energy saving potential. A small-scale three blades IceWind Turbine is designed for the case building. (**Figure 8**) shows designed IceWind blade via Solidworks Software[18] with following measurements; d = 1100 mm, H = 1600 mm plus 500 mm blade tip height, blade angle is 112°, blade's swept area is 999167 mm^2.

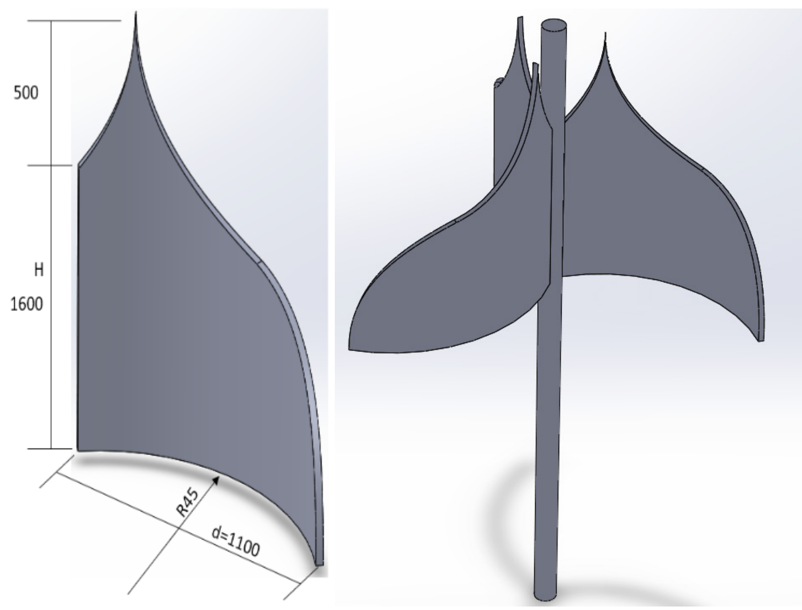


Figure 8. IceWind blade (dimensions in mm)

Within the case building, 40 small-scale wind turbines are installed on the rooftop, while ten columns are structured in a circular arrangement. Each column features ten shafts, with four small-scale wind turbines positioned within each shaft, oriented perpendicular to one another (**Figure 9**). It is worth to note that the design is integrated to DesignBuilder tool by the authors.

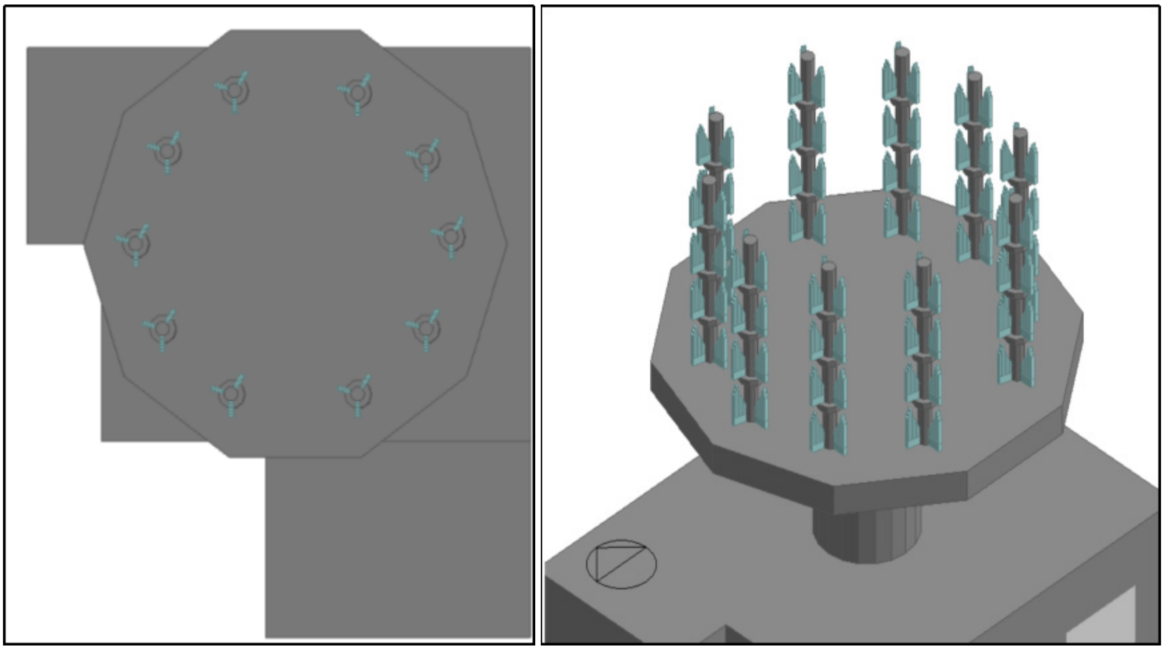


Figure 9. IceWind Turbine Integration to the building

Average wind speed is taken as 4.9 m/s as indicated for Istanbul Airport location. Turbine's efficiency is taken as 59% and the power control is selected as fixed speed variable pitch, from previous parameters the rotor speed is 146 rev/min and rated power output is calculated as 72 watts. (**Table 2**) depicts the input parameters for the building-integrated wind turbines and (**Figure 10**) represents the integration wind turbine parameters to the DesignBuilder Software.

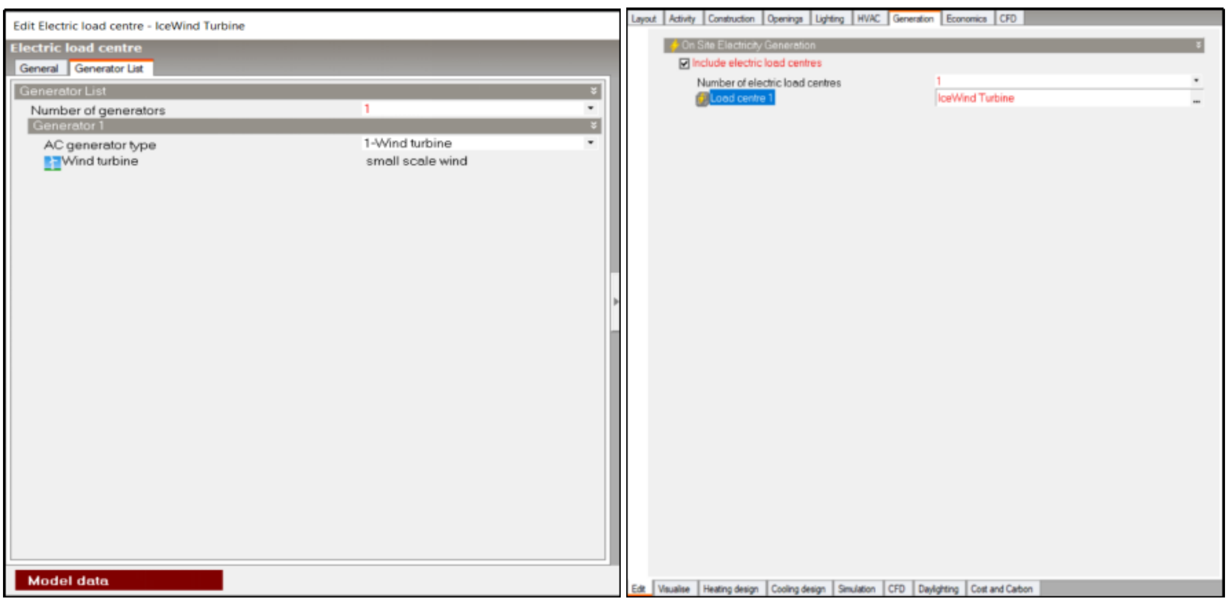


Figure 10. IceWind Turbine Integration to the building

Table 2. Input parameters of wind turbine for the DesignBuilder Software

Input parameter		***Input parameter***	
Operation type	24/7	*Cut in wind speed (m/s)*	3.5
Rotor type	*Vertical axis wind turbine*	*Cut out wind speed (m/s)*	10

Continuation Table:

Input parameter		Input parameter	
Power control	*Fixed speed variable pitch*	*Overall wind turbine system efficiency*	0.59
Rotor speed (rev/min)	146	*Maximum tip speed ratio*	3
Rotor diameter (m)	2.2	*Maximum power coefficent*	0.58
Overall heigh (m)	10	*Annual local average wind speed (m/s)*	5
Number of blades	3	*Blade chord area (m^2)*	3.8
Rated power output (w)	72	*Blade drag coefficent*	0.9
Rated wind speed (m/s)	4.9	*Blade lift coeffcient*	0.05

3. Results and Discussion

The efficiency of the wind turbine is determined through an analysis of the power coefficient. Power of the wind turbines is calculated from following equation:

$$P_{wind} = \frac{1}{2} \times \rho \times A_s \times V^3 \qquad (2.1)$$

ρ = density (kg/m^3)

A_s = Swept area (m^2)

V^3= Wind speed (m/s)

For calculating swept area, the authors used equation (2.2) and calculated the area automatically from the Solidworks Software.

$$A_s = \frac{1}{2} \times L \times (C_t + C_r) \qquad (2.2)$$

L = Blade length ($L = r \times \theta$, where r is the radius of the circular blade and θ is the blade arc angle)

C_t = Chord length at tip

C_r = Chord length at root

Now, the authors utilized equations for the power coefficient (2.3) and wind turbine efficiency (2.4):

$$C_P = \frac{P_{turbine}}{\frac{1}{2} \times \rho \times A \times V_{wind}^3} \qquad (2.3)$$

$$\eta = C_P \times Betz\ Limit \qquad (2.4)$$

Betz limit = 0.593

Therefore, the power of each wind turbine is calculated as 72 W with an approximately 1 m^2 swept area for each turbine. (**Figure 11**) represents hourly power load and energy demand of the case building for a representative day (15^{th} of August). The figure indicates a correlation between the power output of the wind turbines and the energy balance of the building in this scenario, suggesting that this pattern remains consistent throughout the entire year and can thus be utilized effectively.

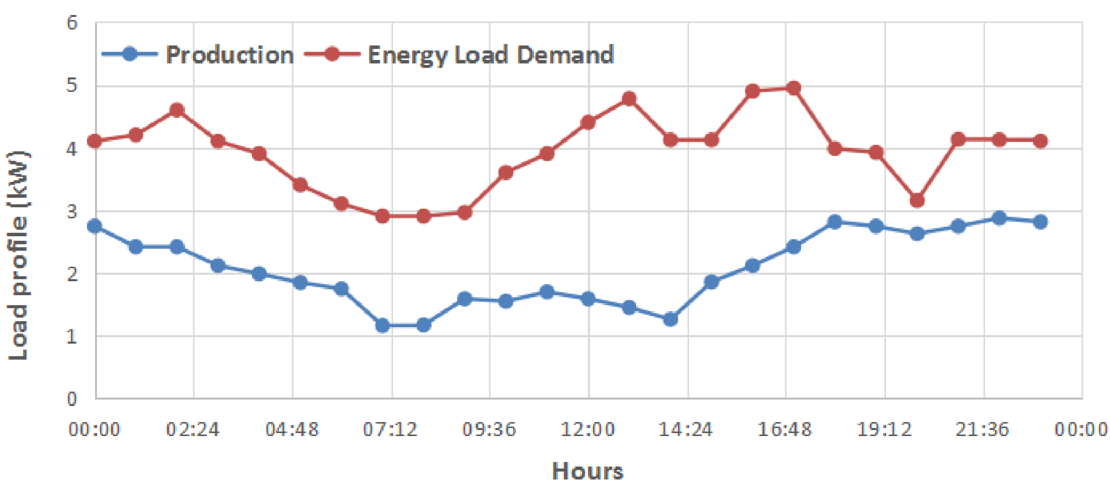


Figure 11. Hourly Production/Demand Energy Balance

The energy consumption of the case building is measured as 175. 45 kWh/m^2 per year and the simulation result is found as 173.41 kWh/m^2 per year and this value show that the model is accurately calibrated. After employing 40 IceWind Turbines equipped with three blades, the simulated building's annual energy consumption is determined to be 157.3 KWh/m^2. In other words, integrating wind turbine to the existing building saved energy by 9.3% per year (**Figure 12**).

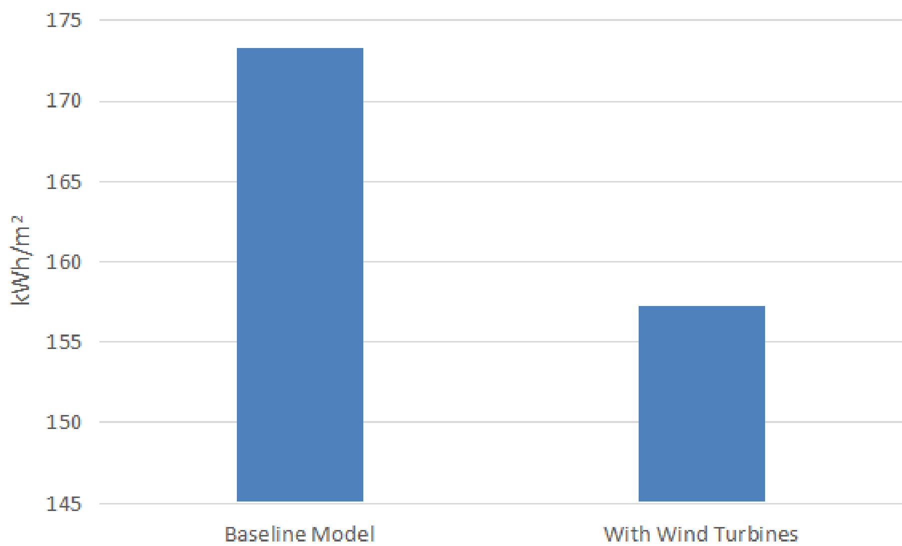


Figure 12. Energy Consumption Comparison of Baseline Model and Wind Turbine Integrated Model

Some discussions on the wind turbine integration to the buildings should be drawn in this section. Calculating wind power for small-scale wind turbines is very challenging. The atmospheric wind is very turbulent in built-up areas, and this is especially intense close to structures and buildings. Therefore, performance of the VAWTs should be discussed in built-up areas due to complex wind conditions[19]. In addition, the noise level could be harm for the birds and occupants in buildings.

The limitation of this study lies in its focus on crafting a new small-scale wind turbine for building integration. Nonetheless, the efficacy of wind turbines in saving energy hinges on diverse design elements like blade swept-area and rotor diameter. Exploring alternative designs may yield superior energy-saving outcomes.

4. Conclusion

This study designed a novel vertical wind turbine and integrated to a case building in order to decrease energy consumption. Details of the selected case building is collected to investigate the energy performance in Istanbul/ Turkey and the DesignBuilder Software is used to model the case building. The results showed that the energy consumption of the building was decreased by using Vertical Axis Wind Turbine as one type of renewable energies strategy, utilizing forty small-scale three blades IceWind Turbines mounted on the rooftop of the case building. The study found that this active solution can lead to 9.3% of reduction in energy consumption. The outcome of this study can help designers, engineers and architects for designing future green buildings.

Conflict of Interest

Declaration of conflict of interest.

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