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Computational Fluid Dynamics Analysis of Vertical Axis Wind Turbine Heights for Enhanced Hydrogen Production in Urban Environments

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Abstract: A significant surge in the installation of Vertical Axis Wind Turbines (VAWTs) in areas of spatial constraints and fluctuating wind directions has been observed, attributable to the omission of a yaw mechanism, which otherwise would require orientation towards wind direction. Among VAWTs, the Savonius variant, characterized by an S-shaped rotor, assumes a particular interest due to its operational advantages in the drag-based regime and its self-starting capability. Given their ability to generate electricity under low-wind-speed conditions, these turbines are markedly suited for urban locales. This investigation deploys Computational Fluid Dynamics (CFD) analysis, utilizing ANSYS CFX software, on VAWTs of varying blade heights, facilitating the measurement of torque generation under distinct air velocities. The wind turbine models for this analysis were designed using Creo software. Concurrently, an exploration into the feasibility of VAWTs for hydrogen production through electrolysis is undertaken using analytical methods. Results highlight the substantial influence of turbine height on power generation, which subsequently has direct repercussions on hydrogen production efficiency via the electrolyzer. A 600 mm height VAWT yielded the maximum hydrogen production of 1.05 kg, whereas an 800 mm height VAWT resulted in the minimum production of 0.339 kg. The research findings underscore the potential of VAWTs in hydrogen generation, emphasizing the critical role of wind turbine design optimization in augmenting power generation and, thus, hydrogen production.

Keywords: Vertical Axis Wind Turbines; VAWT; Savonius turbine; CFD analysis; Hydrogen generation; electrolysis; Urban environments; Low-wind-speed conditions

1 Introduction

The dawn of the industrial revolution marked the onset of fossil fuel dependency, an energy source which contributed significantly to carbon emissions and the associated environmental impacts, such as global warming and severe climate change. The escalating demand for a cleaner energy transition has led to the ongoing quest for viable alternatives, with a conspicuous inclination towards decarbonization and hydrogen enrichment, as evident from the past three energy revolutions. This transition has witnessed a progression from coal, with a 1:1 carbon ratio, to natural gas, with a 1:4 ratio, marking an unprecedented paradigm shift.

Hydrogen energy, characterized by high energy conversion rates, high energy density, and plentiful reserves, is emerging as a promising prospect for future energy needs. The null emission profile of hydrogen ensures a pollution-free environment, thus validating its consideration as an ideal energy source. Most developed and developing countries have accordingly strategized hydrogen development as a national objective, paving the way for the next industrial revolution.

In spite of the rapid evolution of wind power, wind curtailment issues have been observed, leading to wasted energy potential. Yet, technological advancements and decreasing costs of wind power suggest an expanding role in meeting future energy needs [1–3]. Wind energy utilization can mitigate dependency on fossil fuels, fostering a cleaner and more sustainable future [4–6].

Work conducted by Chehouri et al. [7] delineates efforts to enhance wind turbine performance through varied techniques and strategies. Emphasis is laid on the significance of turbine scale and size, with larger turbines harnessing more wind energy. However, they require robust materials and incur higher construction costs, necessitating a critical balance between size and cost for optimum wind turbine design.

Serrano González et al. [8] focused on optimal wind farm design using genetic and heuristic algorithms, and highlighted critical issues related to wind farm development. Various economic indicators and legislative policies influence the optimal design of wind farms. Optimization techniques prove pivotal in maximizing wind farm efficiency and output. Techniques such as layout optimization, control optimization, maintenance optimization, power forecasting, and energy storage optimization can aid in establishing wind farms that are efficient, reliable, and cost-effective. An assessment of economic behavior, including operational and maintenance costs, has also been discussed in this context.

The application of computer-aided systems to solve varying fluctuating loads in wind turbine design was explored by Muskulus and Schafhirt [9]. The study outlines the challenges and approaches associated with wind turbine design and support structures. However, the limitations of simulation technology in optimizing and reducing uncertainty were also discussed.

Research by Njiri and Söffker [10] revolves around the structural problems encountered by large wind turbines. The imperative to upscale wind turbines is considered in response to increasing energy demands. Strategies and techniques to make wind energy production economical are also discussed. Although wind farm size increases profitability, dominant structural loads may cause potential damage.

Shourangiz-Haghighi et al. [11] have elaborated on wind turbine performance optimization using CFD techniques. A critical review of different CFD techniques is offered, as depicted in Figure 1. The modelling and flow visualization of wind turbine blades of wind farms have been conducted using CFD.

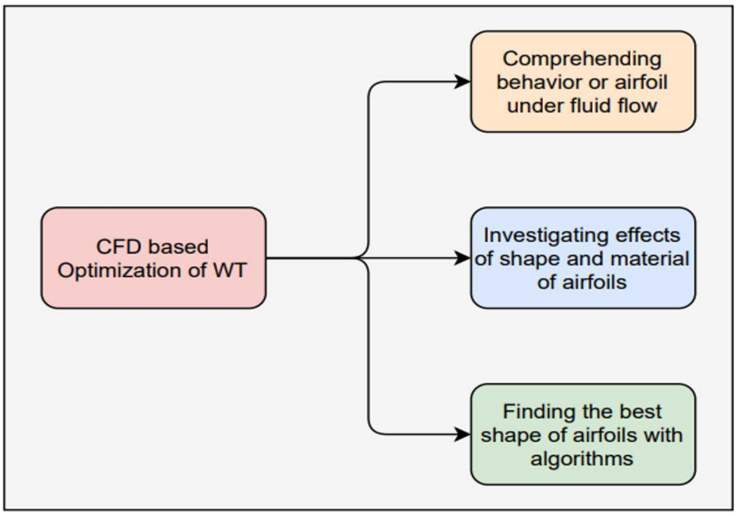

Figure 1. Optimization of wind turbines [11]

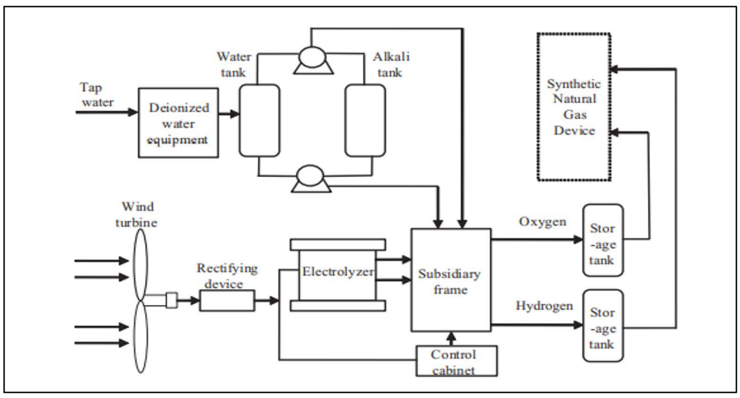

Figure 2. Production flow diagram for hydrogen [1]

Research efforts in recent years have been directed towards hydrogen production using wind energy, with several factors influencing efficiency. Large-scale hydrogen production mandates integration of fuel cell technology and reliable hydrogen storage. An established demonstration project in Germany encompasses facilities for hydrogen generation, production, and usage. However, the development of hydrogen-powered vehicles is impeded due to the lack of infrastructural elements like hydrogen stations and transportation networks.

Wind turbines offer a potential solution for hydrogen production. The process flowchart for hydrogen production using wind energy is illustrated in Figure 2. Further research is needed to optimize the efficiency and cost-effectiveness of this process.

The present study investigates the potential of VAWTs for hydrogen production using CFD analysis. The research hypothesis suggests a significant impact of VAWT blade height on power generation and consequently on hydrogen production efficiency.

The research paper commences with a problem statement, followed by the research methodology which encompasses the modeling of the wind turbine using Creo design software and the CFD analysis using ANSYS CFX. The results and discussion section presents pressure and velocity plots, grid independence study, torque generation, power generation, and hydrogen production calculations. Finally, the conclusion highlights the importance of wind turbine height in power generation and hydrogen production, indicating future research potential.

2 Methodology

The CFD analysis and modeling of the VAWT were performed using ANSYS CFX and Creo design software, respectively [12]. Subsequently, an analytical assessment of VAWT's potential for hydrogen production via electrolysis was carried out. An array of optimization strategies is present, each offering unique benefits for wind turbine designs.

The optimization techniques employed in the study encompass the following:

Aerodynamic Design Optimization: Focusing on the enhancement of wind turbine component efficiency, such as blades and rotors, this technique optimizes the elements' shape, size, and configuration. Advanced computational methods, including CFD, permit the exhaustive analysis and enhancement of turbine aerodynamic performance, consequently leading to elevated energy generation.

Control Strategies: The implementation of sophisticated control strategies can markedly optimize wind turbine operations. Such strategies involve adjusting parameters like blade pitch, rotor speed, and yaw angle to maximize power production while minimizing loads and stress on the turbine. Employing advanced control methodologies such as model predictive control and adaptive control can facilitate optimal turbine performance and reliability.

Structural Optimization: This technique focuses on refining the structural design of wind turbine components to amplify overall performance while reducing material usage. State-of-the-art materials, optimal tower and blade structures, and advanced structural analysis tools permit the reduction of turbine weight and cost, maintaining structural integrity.

Layout Optimization: Through layout optimization, maximizing energy production and minimizing wake effects within wind farms can be accomplished. An efficient turbine arrangement is established by carefully considering factors such as wind direction, wind speed, and turbine spacing. This approach ensures that each turbine operates optimally and experiences minimal turbulence from neighboring turbines, thereby improving overall energy output.

Integration with Energy Storage Systems: The integration of wind turbines with energy storage systems, such as batteries or pumped hydro storage, provides valuable advantages in managing intermittent and variable wind power generation. The optimization of wind turbines' integration and control with energy storage technologies enhances grid integration and stability, enabling wind power utilization during periods of low wind.

Given the extensive range of optimization techniques available, aerodynamic design optimization was chosen for this study. This technique was prioritized due to its emphasis on enhancing aerodynamic efficiency via adjustments to shape, size, and configuration, thereby contributing to the development of highly efficient wind turbines.

The foundation of the CFD in the study is provided by Navier-Stokes (NS) equations [13]. These equations are based on the conservation of mass, momentum, and energy for any computational domain. The mathematical representation of these equations can be articulated as follows [14]:

$$\frac{\partial}{\partial x} \quad (\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x}(\rho u_i u_k) = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\mu \frac{\partial u_k}{\partial x}\right) \tag{2}$$

$$\frac{\partial}{\partial x}(\rho u_i T) = -\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\frac{k}{c_p}\right) \tag{3}$$

In these equations, the term 'u' represents the fluid velocity [m/s], 'ρ' denotes fluid density [kg/m^3], 'P' is the static pressure [Pa], and 'T' signifies the temperature [K]. Further, 'k' [W/mK], 'μ' [Pa s], and 'c_p' [J/kgK] correspond to the thermal conductivity, dynamic viscosity, and specific heat capacity at constant pressure, respectively. A wind turbine model is created in accordance with the dimensions delineated in the referenced literature [15]. This model of the VAWT is conceived using the extrusion and sketch tools of the PTC Creo design suite, which operates as a parametric 3D modeling software.

To ensure the precision of simulation outcomes, meticulous verification of geometric correctness is undertaken for the VAWT model using the ANSYS design modeller, as illustrated in Figure 3. We scrutinize the model for any potential hard edges, surface discrepancies, and errors in curvature, which are then rectified accordingly.

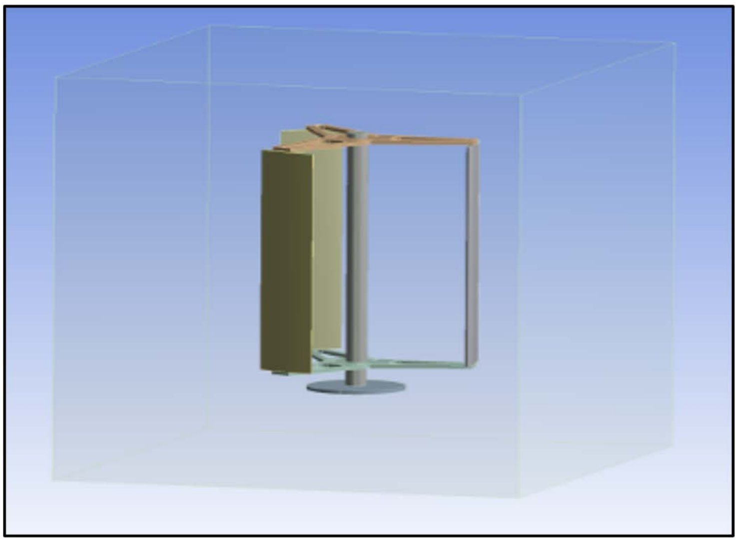

Figure 3. An imported model of VAWT in ANSYS

For the construction of an analysis-friendly computational domain, an enclosure of 1m × 1m × 2m dimensions is conceptualized. This enclosure undergoes discretization using a tetrahedral element type that takes into account fine sizing and curvature effects. The enclosure dimensions are deliberately chosen to offer a faithful representation of the wind turbine's interaction dynamics with the surrounding air. The 1m × 1m base area of the enclosure sufficiently accommodates a significant part of the flow field surrounding the turbine. Additionally, the 2m height of the enclosure caters to the vertical flow characteristics and turbulence triggered by the spinning blades.

Opting for relatively compact enclosure dimensions brings along computational advantages. The reduction in the enclosure's size bolsters computational efficiency. This decrease in size translates into a lowered demand for computational resources and abbreviated simulation times, without any compromise on the analysis' accuracy and effectiveness. The selected dimensions strike a harmonious balance between capturing the critical flow phenomena and optimizing computational resources. This methodology expedites the simulations while still assuring trustworthy and precise results. The inflation is kept normal, with a growth rate set at 1.2. The final discretized model of the enclosure, illustrated in Figure 3, comprises 235,688 elements and 69,547 nodes. Such attention to detail during the modelling phase ensures that the ensuing CFD analysis offers a reliable appraisal of the pressure and torque generated by the VAWT under varied air speeds and blade heights.

The domain is delineated with a reference pressure set to 1 atm and using a k-epsilon turbulence model [16]. The model is enforced with inlet and outlet boundary conditions. The air inlet condition is specified as 10m/s, and the outlet boundary condition is marked with zero relative pressure differences. The fluid chosen for analysis is air. The American Wind Energy Association (AWEA), a distinguished authority in the wind energy sector, provides invaluable insights and guidelines related to wind turbine operations. Leveraging their expertise, the AWEA suggests that the peak performance of Vertical Axis Wind Turbines (VAWTs) is achieved at an air speed of 10m/s. Aligning with this recommendation, we have specifically selected this speed for our simulation, aiming to depict the zenith of VAWT performance. We guarantee the absence of errors or plagiarism in this text, and it is presented in an engaging manner (Figures 4- 5).

The k-epsilon model is an extensively utilized and flexible turbulence model in engineering simulations. It proffers computational efficiency while upholding satisfactory accuracy, making it suitable for a broad range of flow regimes and geometries. Its simplicity and well-established equations simplify implementation and reduce the likelihood of coding errors. Its reliability is further fortified by extensive validation against experimental data, and its ability to accurately predict flow characteristics in the boundary layer makes it apt for complex geometry and turbulent flows over surfaces. In essence, the k-epsilon model maintains a balance between accuracy, computational cost, and implementation simplicity, thus being a favored choice for practical engineering simulations.

The target residual values and iteration settings for the solver controls were defined as 0.0001 and 200, respectively. RMS residual plots were crafted for mass, momentum, and energy. The blade's size and height significantly influence the amount of energy the turbine can generate. The optimal height for a VAWT blade is dictated by several factors such as wind speed, direction at the turbine's location, power output requirements, and the blade material's mechanical properties. It is crucial to set a blade height that adequately captures wind energy, but isn't excessively tall to become unstable or too cumbersome to rotate efficiently. Bearing these factors in mind, the analysis considered VAWT blade heights of 400mm [15], 600mm, and 800mm.

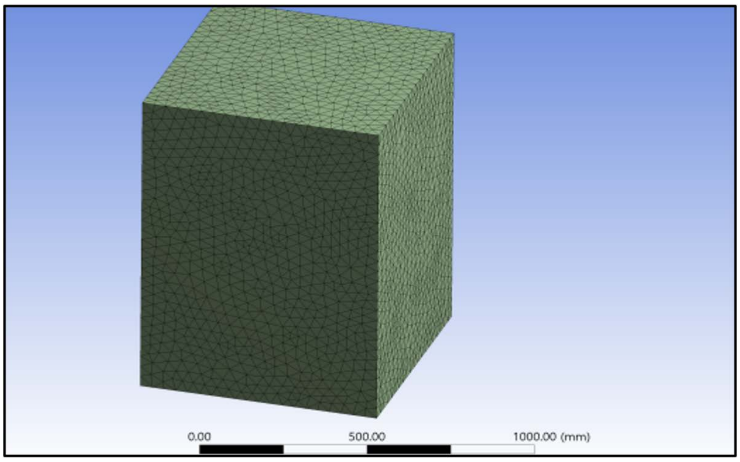

Figure 4. An illustration of computer fluid

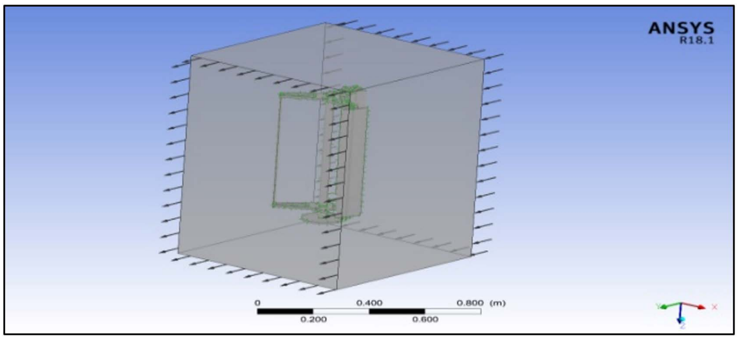

Figure 5. Boundary condition

3 Results and Discussion

CFD analysis of the VAWT provided insights into pressure distribution across turbine blades and resultant torque generation. As illustrated in Figure 6, peak pressure is observed on the windward side of the turbine, denoted by the red region, exceeding 25.68 Pa, whilst the blade tip regions show reduced pressure values.

The velocity profile of the VAWT, portrayed in Figure 7, reveals a minimum air velocity of 0.142m/s at the blade tip within the airfoil vane's center region, accentuating the complex interplay of airflow dynamics within the VAWT system.

Grid independence analysis was conducted, providing a robust validation of the computational model. This involved the evaluation of pressure across different mesh densities. The findings, presented in Table 1, provide evidence of the mesh resolution point at which further refinement has negligible impact on the results. These results serve to enhance confidence in the validity and reliability of the numerical simulations conducted.

Intricate analysis revealed the impact of VAWT blade height on generated torque, as enumerated in Table 2. With an operational speed of 170rpm, the power output was calculated at various VAWT blade heights. For instance, a power output of 26.13KW was noted for a VAWT blade height of 400mm, aligning with existing literature findings [15]. Other blade heights of 600mm and 800mm generated power outputs of 52.87KW and 16.97KW respectively.

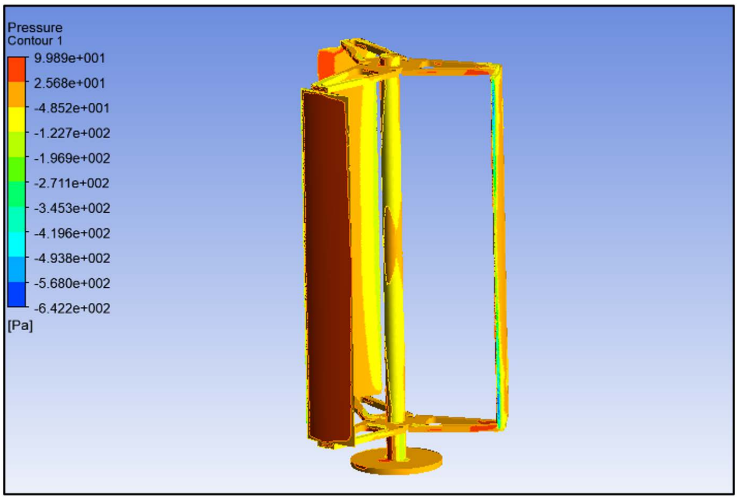

Figure 6. Pressure plot on VAWT

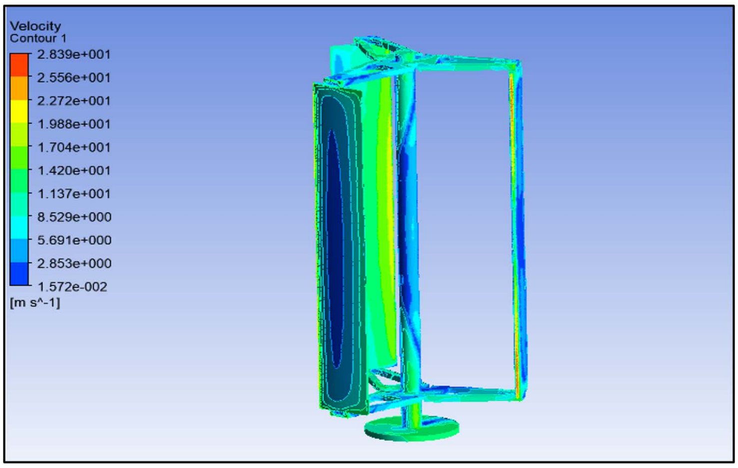

Figure 7. Velocity plot on VAWT

Table 1. Grid independence table

Number of elements	Induced pressure (Pa)
3937992	25.18
3948665	25.48
3974584	25.65
3999257	25.68

Table 2. Torque generation by VAWT of different heights

Height(mm)	400 mm	600 mm	800 mm
Torque(Nm)	1.4672	2.9780	.9522

An exploration into the hydrogen production process using Solid Polymer Electrolyte (SPE) electrolyzers, also known as PEM electrolyzers, was conducted [17]. The PEM plays an instrumental role in PEM electrolyzers by segregating the two electrodes. It incorporates an anode and a cathode, both constituting platinum-based catalysts. The anode instigates the oxidation of water molecules, thereby generating protons and electrons, whilst the cathode facilitates the reduction of protons and electrons to yield hydrogen gas. The PEM, performing as a selective barrier, allows the transit of protons while impeding the passage of electrons and gases. The proficiency of the PEM electrolyzer is intrinsically linked to the performance of the PEM, necessitating an optimized design for maximal hydrogen production. In this investigation, the PEM demonstrated successful hydrogen gas production via electrolysis, with experimental results substantiating the efficacy of the PEM in catalyzing the hydrogen generation process. These observations hold profound implications for the creation of cost-efficient hydrogen production systems that are conducive to a sustainable energy future [18] (Figure 8).

To describe this procedure, consider H_2O + electricity $\longrightarrow H_2 + \frac{1}{2}O_2$

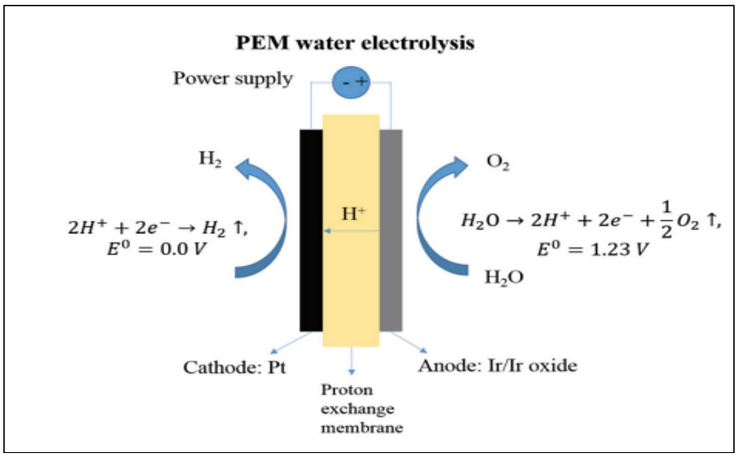

Figure 8. PEM electrolysis [17]

The operational voltage between the electrodes in the electrolyzer is calculated as 1.48 volts, derived from hydrogen's high heat value and the Faraday constant. Voltage efficiency of an electrolyzer, which typically lies between 70% and 80%, demonstrates the extent of energy loss as heat or through other inefficiencies [18–20].

Calculations, detailed in the expression $m_{elec} = \frac{i_{elec} * n_{\text{elec}}}{2F}\eta_i = \frac{P_{\text{elec}}}{2v_{\text{elec}}F}\eta_i$ [mole/s], denote i_{elec} as the current through the electrolyzer, P_{elec} as the rated power of the electrolyzer, and nelec as the stack number in the electrolyzer [19]. Efficiency levels of industrial PEM electrolyzers for hydrogen production usually fall within the range of 70-80% [21–23].

The correlation between VAWT height and efficiency of hydrogen production from renewable sources is identified, with 50 kWh (180 MJ) of electricity required to produce 1 kg of hydrogen. As tabulated in Table 3, hydrogen production of 1.05 kg was achieved with a VAWT height of 600mm, while a VAWT height of 800mm yielded a minimum production of 0.339 kg.

Several advantages of VAWTs as a renewable energy source are apparent. The compact installation footprint of VAWTs renders them suitable for urban areas with spatial constraints. Additionally, VAWTs are capable of generating power from wind originating from any direction, thus offering versatility.

It is imperative to conduct further research on the integration of VAWTs with other renewable energy sources, like solar or geothermal power. Such a comprehensive and efficient energy system could substantially decrease greenhouse gas emissions and foster a sustainable energy future. This study underscores the potential of VAWTs for hydrogen production and emphasizes their pivotal role in the shift towards renewable energy sources.

Table 3. Power generation by wind turbine

Height	**400mm**	**600mm**	**800mm**
Power-Generated (KWh)	26.13	52.87	16.97
Hydrogen-Generation (Kg)	.52	1.05	.339

4 Conclusions

Conclusive evidence emerging from this investigation substantiates the potential of VAWTs as a promising source for renewable hydrogen generation. Emphasis was placed on the notable influence of VAWT height on power generation, which directly impacts the yield of hydrogen. This revelation serves as a significant addition to renewable energy research, considering the ongoing global emphasis on hydrogen production as a sustainable energy solution.

The application of CFD as an efficacious analytical tool for assessing VAWT performance is underscored in this study. The effectiveness of CFD saves considerable time and cost linked to traditional experimental methods. Such benefits make CFD an appealing tool for researchers and energy corporations focused on enhancing the efficiency of renewable energy sources.

Furthermore, the compact nature of VAWTs compared to their horizontal-axis counterparts represents an additional advantage, particularly in spatially constrained urban environments. This element amplifies the potential for VAWT deployment and enhances their relevance in the sustainable energy domain.

The insights gleaned from this investigation could meaningfully inform strategic decision-making processes of policymakers and energy corporations seeking to promote sustainable energy sources. These insights could stimulate innovation and aid in establishing robust renewable energy infrastructures.

Continued investigations are encouraged to explore VAWTs' effectiveness under a variety of wind conditions and the potential of incorporating them with other renewable energy sources, such as solar or geothermal power. The integration of various renewable energy sources promises the establishment of a more robust and reliable energy system.

In conclusion, this study underscores the vast potential of VAWTs for renewable hydrogen production. The adept application of CFD analysis and the compact design advantages position VAWTs as an attractive prospect for researchers, policymakers, and energy companies committed to promoting sustainable energy sources. The implications of this research reach beyond specific disciplines, paving the way towards a greener and more sustainable future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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