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# WIND ENERGY-BASED HOT WATER PRODUCTION: COMPUTATIONAL APPROACHES

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## Abstract:

Wind-powered hot water production has received a lot of attention as a green and sustainable option. In this study, we investigate the computational strategies needed to convert wind energy into hot water. Wind resource assessment, turbine design/sizing, wind farm layout optimization, power conversioncontrol, system modeling/simulation, energy managementoptimization, and so on are all covered by the techniques. Engineers are able to more effectively manage energy consumption with the help of simulations of system performance, optimizations of turbine designs and layouts, management of electricity conversion for water heating, and more thanks to the availability of powerful computational tools. These computational techniques allow for the effective use of wind energy for hot water production, which in turn helps to create a more sustainable energy future.

**Keywords:** Heat Transfer, Air Conditioning, Fluid Mechanics, Hydraulic, Turbine Pump, Wind Power

## Introduction:

Providing for the world's energy needs in light of recent climate change is a challenging challenge. Renewable energy will supplement or ultimately replace traditional power sources. Wind energy, being both plentiful and renewable, seems like a good option. However, large-scale wind turbines, especially when grouped together in enormous wind farms, may have a detrimental effect on the environment and weather [1]. Because of this, there is a significant potential for profitable power generation from dispersed and decentralized small-scale wind turbines. Without affecting the climate or ecosystem, they can provide enough for basic household requirements [2].

The properties of tiny wind turbines, as well as their limits and drawbacks, must be understood. The high upfront cost, the significance of site assessment (resulting in efficient wind turbine placement) [3, 4], awareness of wind conditions at the site (wind velocity and direction, seasonal changes), and aero-acoustic noise are the most frequently cited challenges. However, when appropriately designed and operated, modest wind turbines may be seen as a beneficial and eco-friendly power source. From a financial perspective, the initial cost per unit power and the unit cost per unit energy it generates [5] are both critical.

The Generative Urban Small Turbine (GUST) project is designed to meet these needs by having students construct a horizontal axis wind turbine with a swept area of 2 m2 and a notional power output of around 750 W. The group has competed in and won three consecutive years (2016-2018) of the International Small Wind Turbine Contest. The biggest innovation proposed by GUST concerns the aerodynamic design of wind turbine blades followed by manufacturing them using 3D printing methods; this is in addition to self-constructed mechanical components (e.g., hydraulic brake), modifications of the generator (coil switching system), and self-designed control and safety systems.

Some have called fast prototyping an industrial revolution [5]. It allows for immediate movement from the design phase to manufacturing. Despite the benefits shown [6, 7], more research is needed before additive manufacturing may be widely used in the fabrication of tiny wind turbine blades. The GUST project at the IMP TUL used 3D printing to make scaled-down versions of wind turbine blades. The aerodynamic characteristics of the selected airfoils were then evaluated by testing scaled models in an in-house wind tunnel. SLA technology was employed to produce the most promising geometries, which were then used in the final, full-scale prototype.

## Computational methods

Several key components of turning wind into hot water rely heavily on computational approaches. Wind resource evaluation, turbine design and size, wind farm layout optimization, power conversion and control, system modeling and simulation, energy management and optimization, and so on are all included in these techniques. Computational tools and methods allow engineers to precisely evaluate wind resource potential, improve turbine design and layout, convert and regulate power for water heating, model system performance, and dynamically manage energy consumption. With the help of these computational approaches, wind energy may be used effectively and efficiently, leading to ecologically friendly and sustainable hot water production [8].

## Wind energy

Using the kinetic energy of the wind to create electricity is the basis of wind energy, a sustainable and clean power source. Wind power production is the process by which kinetic energy from the wind is transformed into electrical energy by use of wind turbines, which have huge rotor blades. Reduced emissions of greenhouse gases, lessened effects of climate change, and the possibility of energy autonomy are just a few of the many advantages of this sustainable energy source. The potential to produce power from wind exists in both onshore and offshore settings, and its availability is widespread. Wind energy plays a critical role in diversifying the energy mix and fostering a cleaner, more sustainable world as part of the transition to a greener and more sustainable energy future [9].

## Wind Resource Assessment:

The potential of wind resources in a given area is evaluated using computational methods. The average wind speed, wind power density, and wind energy production potential of the location may be determined by using these tools, which evaluate historical wind speed and direction data. This data is useful for determining where to put wind turbines [10].

## Wind Turbine Design and Sizing:

Designing and sizing wind turbines for hot water generation through computational approaches. The number of turbines, their power output, and the best configuration for maximizing energy harvesting are all factors to be considered. Different turbine designs may be evaluated, and their performance can be optimized, with the use of software tools like turbine performance simulators and computational fluid dynamics (CFD) simulations [11].

## Wind Farm Layout Optimization:

Computational approaches are utilized to optimize the placement of several wind turbines within a wind farm for larger-scale hot water generating systems. To optimize energy output and reduce losses due to wake effects, these strategies take into account variables including topography, weather, and wind direction fluctuation [12].

## Power Conversion and Control:

To warm water, one must first convert and regulate the power produced by wind turbines. In order to stabilize the DC electricity that is generated by wind turbines, inverters and rectifiers must be designed and optimized using computational techniques [13]. Algorithms for controlling the flow of electricity and the water temperature are also created.

## System Modeling and Simulation:

The effectiveness of the whole hot water production system is evaluated with the use of computational modeling and simulation techniques. Wind speed, turbine features, power conversion efficiency, heat transfer qualities, and water storage capacity are just few of the many variables taken into account by these models [14]. Energy output and hot water production can be predicted, system behavior can be understood, and design parameters may be optimized with the use of simulations.

## Energy Management and Optimization:

Using computational methodologies, energy management in the system may be improved. Optimization of wind turbine and hot water storage functioning is achieved by evaluating real-time data from wind sensors, weather predictions, and energy demand trends [15]. Dynamically adjusting the system parameters using methods like predictive control algorithms and machine learning may optimize the use of wind energy for hot water production.

## Current methods of cooling wind turbines:

A lot of heat is generated by the wind turbine's gearbox, generator, and control system during operation [16]. Wind turbines need efficient cooling measures applied to its components to guarantee safe and steady operation. Due to the lower power output and thus lesser heat generation of early wind turbines, the cooling demand could be handled using just natural air. Increases in electricity output mean that open windows and fans aren't enough to keep things cool. Forced air cooling and liquid cooling are two common cooling methods for modern wind turbines. For wind generating sets with a power rating of less than 750 kW, forced air cooling is often used. A liquid recirculation cooling system may be devised to meet the cooling need [16] for large and medium-scale wind generating sets with power greater than 750 kW.

## The Wind System and Transmission:

The wind generator had three FRP vanes, each measuring 1.6 meters in length. The bearing and pulley system secures the central axis to the frame. A gearbox with a 1:5 gear ratio is mounted in the chassis [17]. The pulley mounted on the wind turbine's central axis and the pulley used for transmission have a diameter ratio of 5:1, meaning that the wind turbine's rotation speed may be multiplied by 1:25 in order to power the heat pump's compressor.

## The Heat Pump System:

In the figures provided, we see that the heat pump system had the following components: an open-type compressor; a condenser; a capillary; an evaporator; a start control valve; and a four-way valve. The wind turbine's control valve is open at starting, allowing air to flow freely between the compressor's discharge and suction ports. When the wind turbine's rotation speed reaches its maximum speed, the start control valve is gradually closed, allowing the compressor to begin functioning at full capacity and the coolant to begin circulating in the cooling system. In this test, the heat pump's cooling capacity is 0.5 kW and its heating capability is 0.6 kW [17].

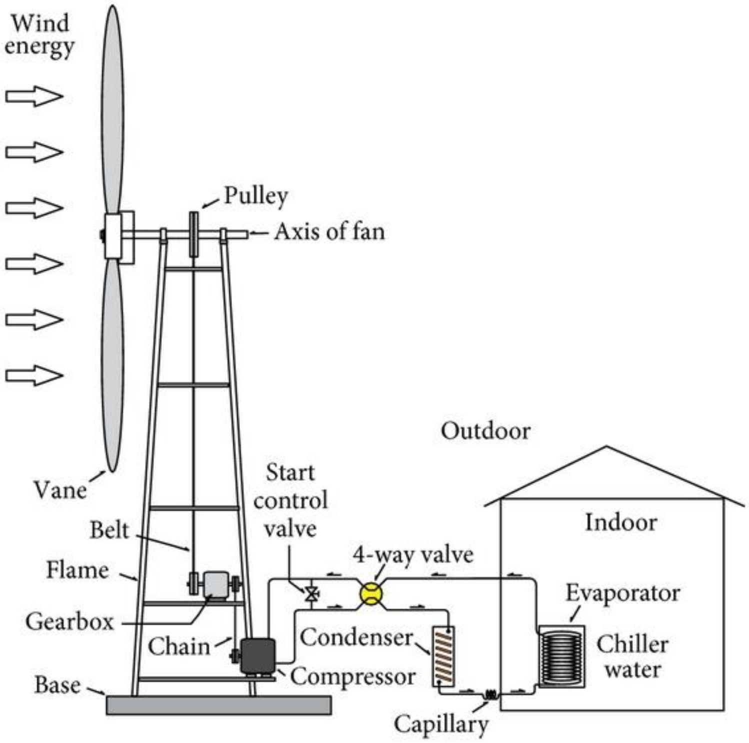

**Figure 1: Wind Summer model (chiller)**

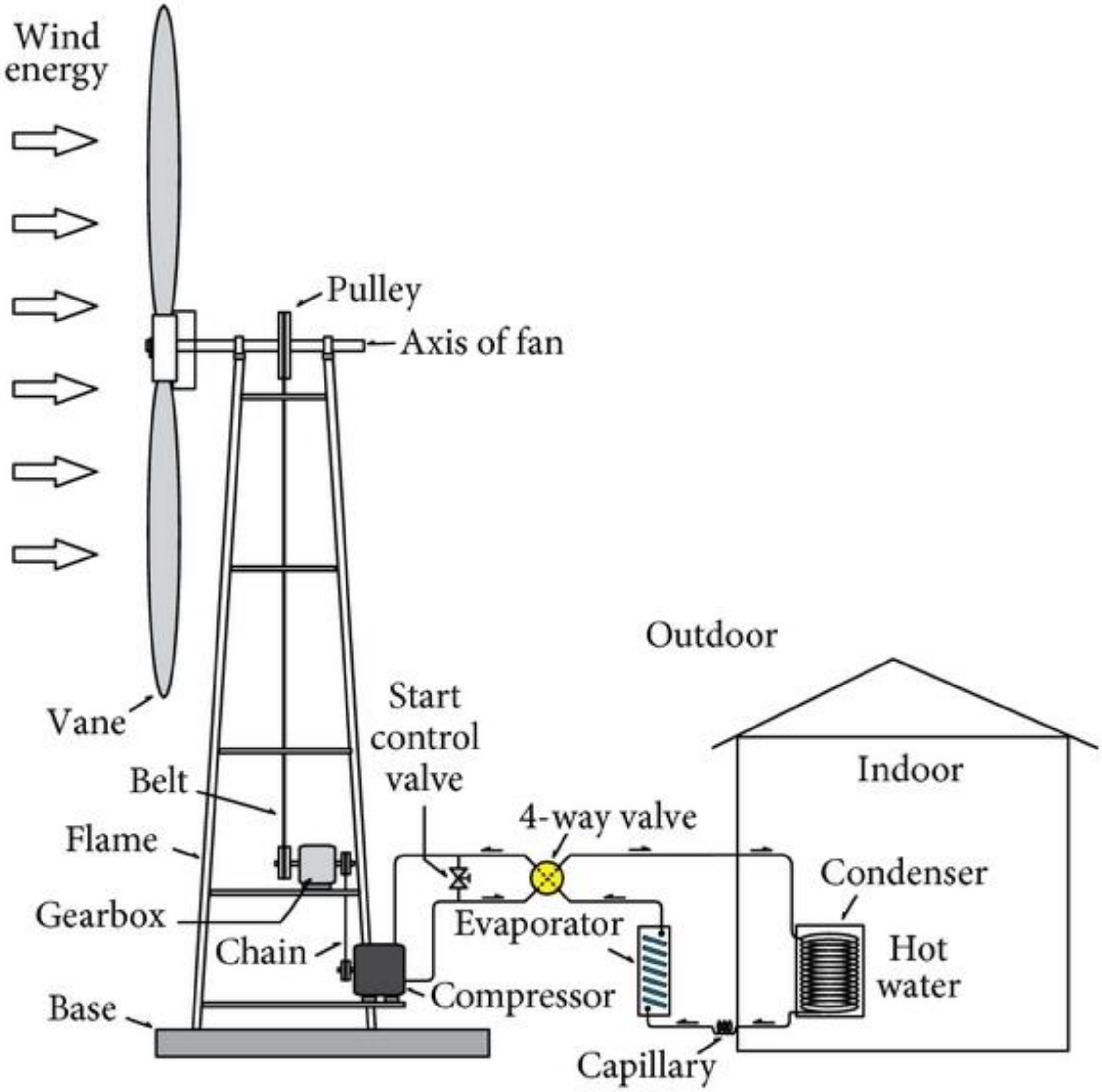

**Figure 2: Wind Winter model (heat pump)**

There are two distinct experimental strategies used. The interior heat exchanger acts as the evaporator and the outside heat exchanger as the condenser in the summertime model, as seen in the figure. The interior heat exchanger acts as the condenser and the outside heat exchanger as the evaporator in the winter model, as seen in the figure. To switch between the two experimental versions, just turn the 4-way valve. Temperatures of 35 degrees Celsius outside and 25 degrees Celsius inside are used in the summer model, whereas temperatures of 10 degrees Celsius outside and 10 degrees Celsius inside are used in the winter model [18].

As can be seen in Figure 3, the experimental device's measuring system looks like this: (is the compressor's suction pressure, (is the compressor's discharge pressure, (is the compressor's discharge temperature, (is the condenser's outlet temperature, and (is the evaporator's inlet temperature). Experiments are conducted at average wind speeds of 3, 4, 5, and 6 meters per second, with the aforementioned measurement locations linked to the data logger. In this setting, reliable information might be retrieved from a computer and utilized as a debate starting point [18].

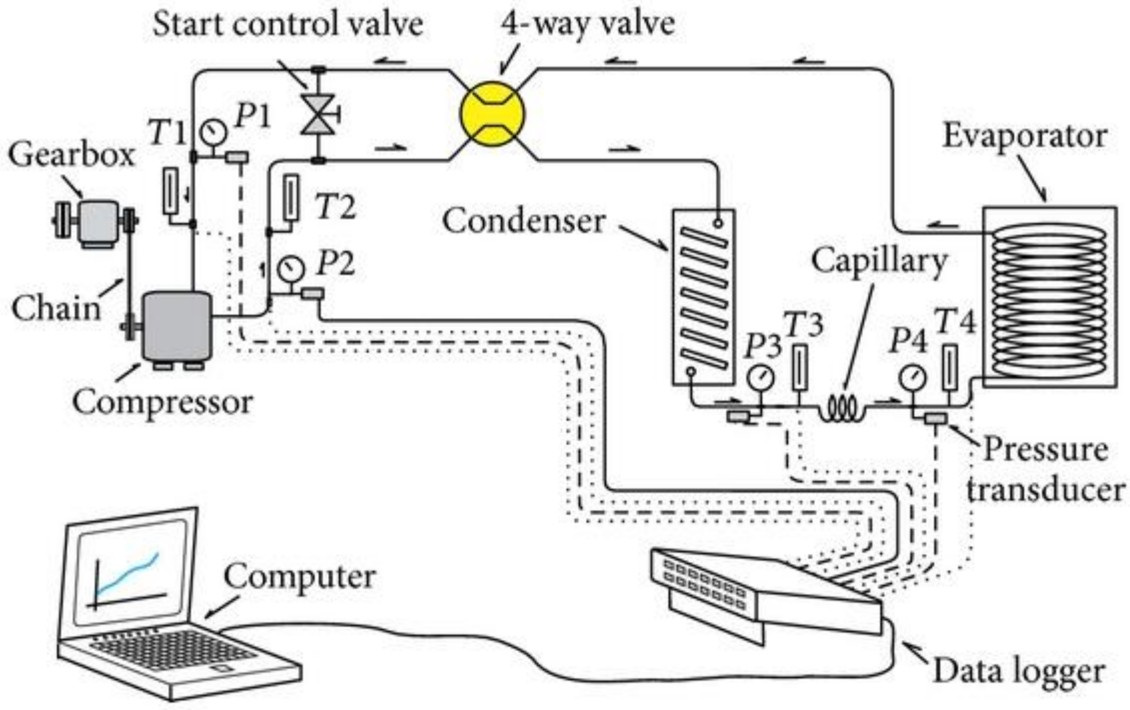

**Figure 3: Measure system and experimental device**

## Material and Method:

The investigation employs a heat pump technology powered by wind turbines. Because of this need, engineers developed a heat pump technology that is powered by wind turbines. The wind turbine, heat pump, and pulleys are shown in this diagram as the system's three main components. The wind turbine has a diameter of 2.6 meters thanks to its tower and two rotor blades. Power is transferred from a wind turbine's driver pulley, placed on a blade, to the turbine's driven pulley, at its opposite end, using a series of V-belts. The main components of a heat pump include the compressor, condenser, evaporator, capillary tube, filter, and many more. Mechanical energy is transmitted from the driven pulley to the open type rotary compressor via a shaft.

In a traditional heat pump system, the water supply enters from the shell side and passes through the tube coil while being heated by the discharge gas from the compressor. A rotameter is set up upstream of the condenser to measure the water's volumetric flow rate. The temperature of the shower water may be measured using a thermometer. To further control the water flow, ball valves were installed at the heat exchangers' inlets.

### Wind turbine

The relative wind angle (φ) in respect to the rotation of the wake may be calculated using Eq. (1).

$$\varphi = \left(\frac{2}{3}\right) \tan^{-1}\left(\frac{1}{\lambda}\right)$$

……(eq.1)

**Where, $\lambda$ represents the tip speed ratio**

### Heat pump

Based on heat transport and thermodynamics principles, a mathematical model of the heat pump system is analyzed. Engineering Equation Solver (EES) was used to model the performance of the current heat pump setup.

### Validation study

The efficiency of the wind turbine that powers the heat pump was used to verify the present computation with the findings from the previous literature. Therefore, proof is being based on the results of this investigation. Close agreement may be found between the two data sets. In conclusion, the excellent agreement between the compared data provides support for the existing estimates. As a result, the current CFD model does not need to be scrapped.

## Results:

### Power coefficient of Wind turbine

Using MATLAB, we have determined the output power of a 2.6-meter-diameter, upwind, horizontal-axis, wooden-bladed wind turbine rotor spinning at an optimal speed. Figure 4 and 5 shows the ( $C_p$ ) relationship between TSR and wind at 5º and 10º angles of attack speed, respectively.

At a given TSR and wind speed, the maximum ( $C_p$ ) power coefficient varies throughout the curves. The findings show that when TSR and wind speed rise, the power coefficient falls. At 10 degrees of attack, 4 TSR, and 6 meters per second, the greatest value of ( $C_p$ ) was produced, which is around 0.54. The opposite is true at a wind speed of 9 m/s and a tip speed ratio of 10. This minimal value of was found at an angle of attack of 5 degrees.

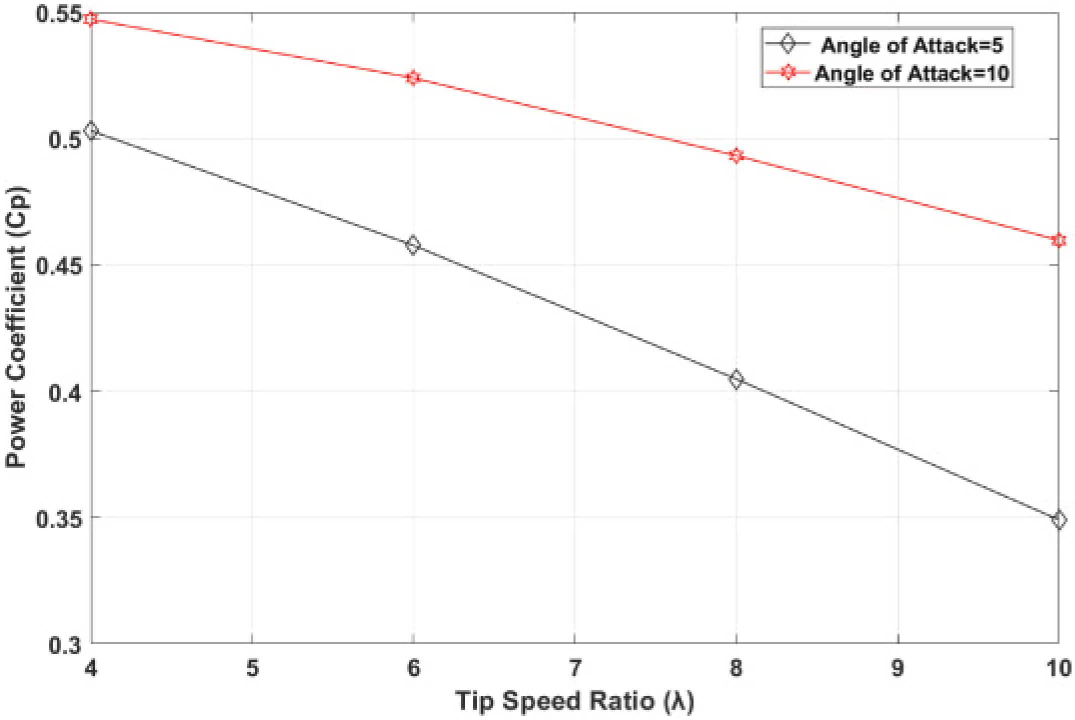

**Figure 4: Power coefficient ( $C_p$ ) versus tip speed ratio Changing**

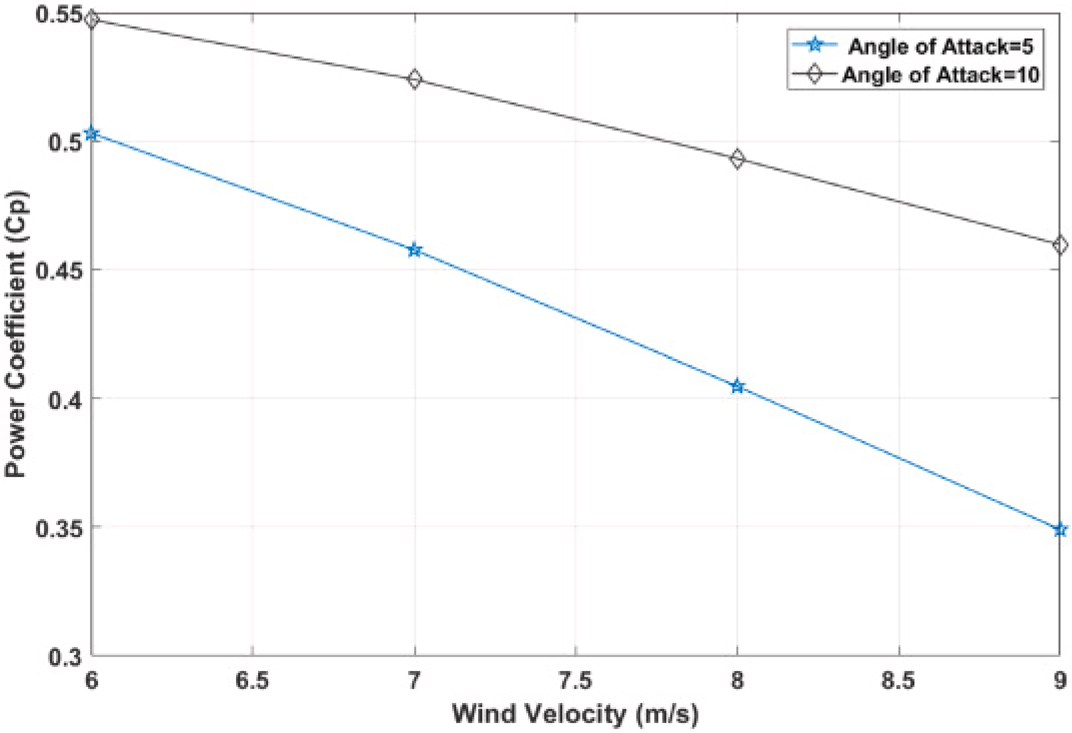

**Figure 5: Power coefficient ( $C_p$ ) versus wind speed Changing**

**Output power of wind turbine**

Figure 6 depicts the power curve at two angles of attack at wind speeds between 6 and 9 meters per second. Power production from the wind turbine was found to rise with wind speed, with a maximum power output of roughly 1.1 kW at 9 m/s and 10 $^{o}$ angle of the attack, while $C_p$ taking into consideration at 10 TSR. At the same wind speed and angle of attack, the $C_p$ output power is around 0.83 kW. The output of a wind turbine is proportional to its rotational speed and the wind speed.

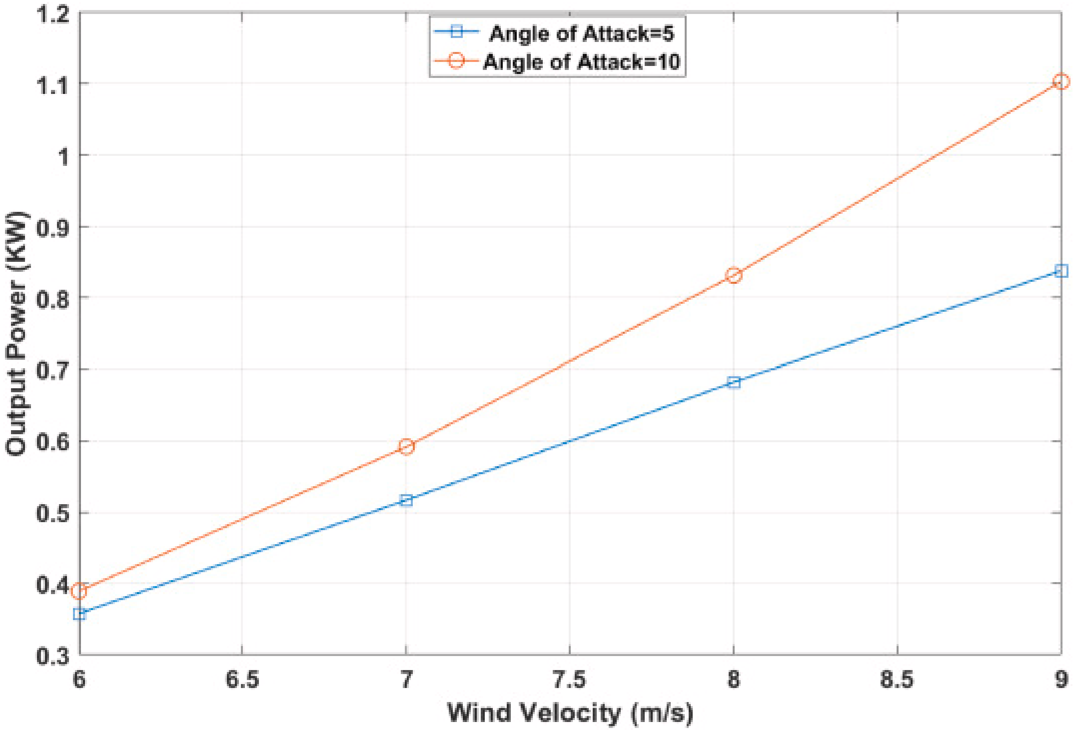

**Figure 6: Wind turbine poweroutputversus wind velocity**

### Torque analysis of Wind turbine

Figures 7 and 8 depict the torques at two different angles of attack as a function of wind speed. It is evident that the rotor torque significantly affects the wind turbines performance. It is shown without any reasonable question that the torque value is favorably affected by both wind speed and angle of attack. Higher wind speeds allow for greater amounts of energy to be delivered from the wind to the turbine's blades. The outcome is increased torque and a higher rate of rotation for the blades. When the blade's angle of attack increases, so does its lift, resulting in a greater rotational speed and torque. Peak torque produced by the wind turbine is calculated to be about 10.23 Nm at 5° angle of attack and 28.1 Nm at 10° angle of attack for the higher value of wind speed (7 m/s).

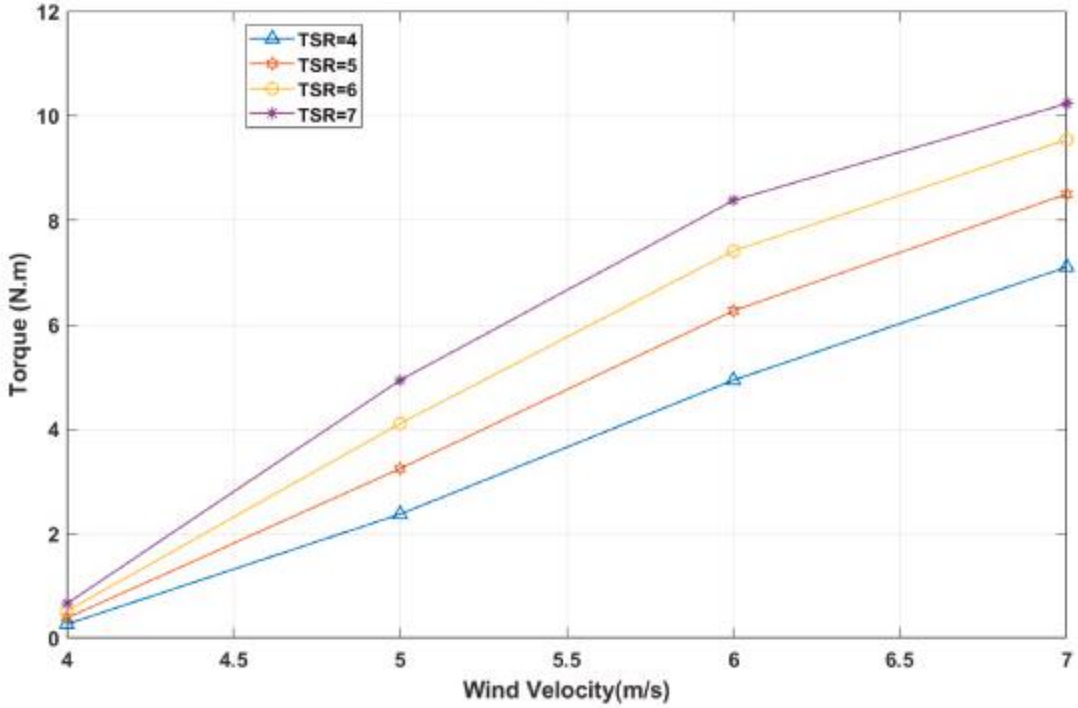

**Figure 7: Torque produced by the rotor as a function of wind speed at an attack angle of 5 degrees**

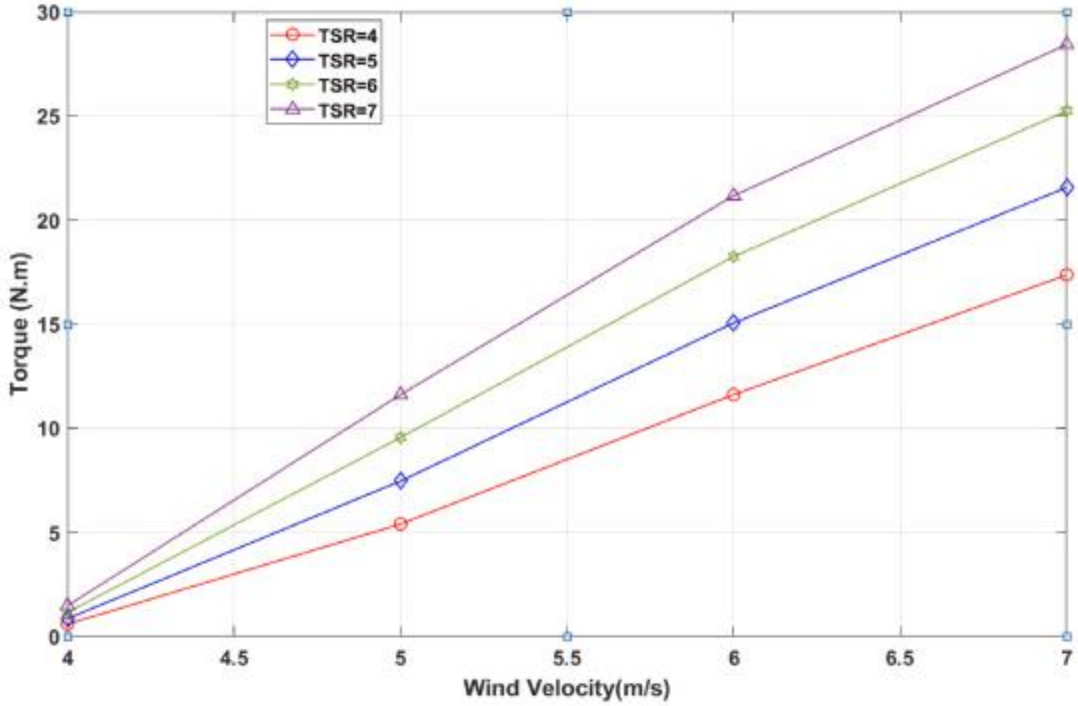

**Figure 8: Wind speed against rotor torque at a 10 degree angle of attack**

**System analysis of Heat pump**

It is assumed that the mechanical power produced by the wind turbine is equivalent to the power needed to run the heat pump compressor. When the wind speed was 6, 7, 8, and 9 meters per second, the results were 0.35 kW, 0.51 kW, 0.68 kW, and 0.83 kW, respectively, at an angle of attack of 5o. Results were 0.39 kW, 0.59 kW, 0.83 kW, and 1.1 kW at an angle of attack of 10 degrees. It was believed that the evaporator temperature would stay at 5 degrees Celsius over a range of condenser temperatures from 30 to 50 degrees Celsius. In Fig. 9, we can observe how the COP affects the water temperature at the condenser's outlet. Power at a 5o angle of attack is shown by the red dots, while power at a 10o angle of attack is depicted by the blue dots.

It is also evident that as the temperature of the condenser's outflow water increases, so does the COP. However, when the condenser saturation temperature is increased from 30°C to 50°C, the COP and water outflow temperature from the condenser both decrease. Maximum COP of around 4.1 was recorded at 30 degrees Celsius condenser temperature.

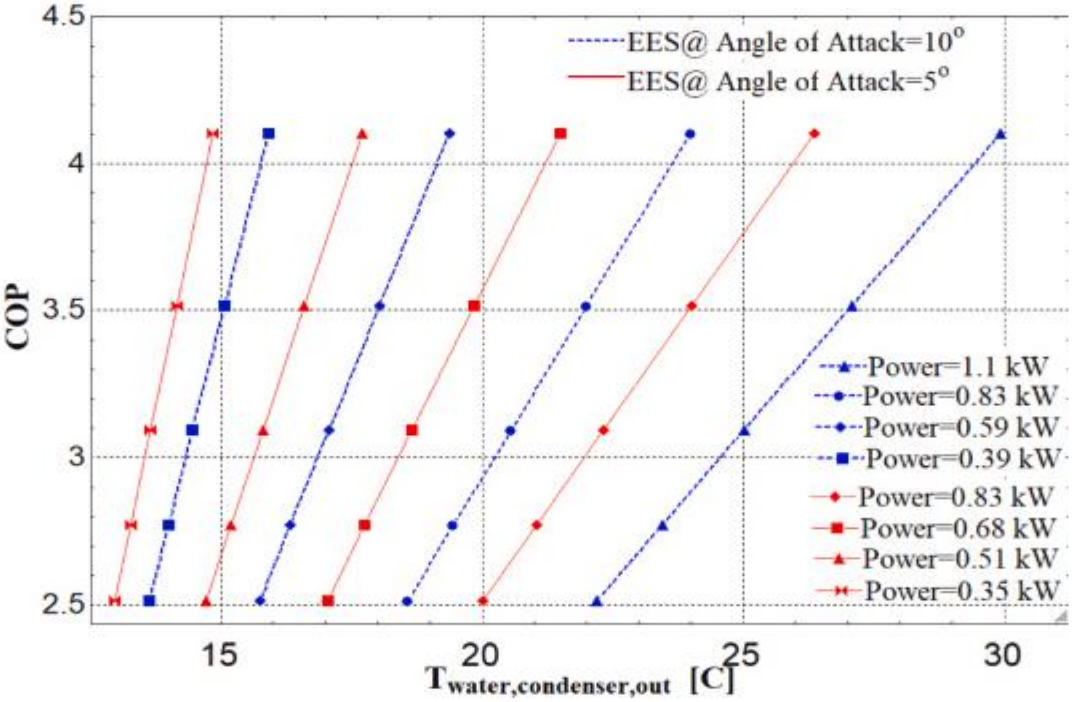

**Figure 9: The coefficient of performance (COP) vs condenser water temperature**

## Conclusion:

Computational methods play a critical role in the production of hot water using wind energy. Through the application of these methods, engineers can effectively design, optimize, and control wind-powered systems for water heating. The use of computational tools allows for accurate assessment of wind resources, efficient turbine design and sizing, optimized wind farm layout, precise power conversion and control, realistic system modeling and simulation, and dynamic energy management. By harnessing the power of wind energy through computational methods, we can promote sustainable and environmentally friendly hot water production, reducing reliance on conventional heating methods and contributing to a greener energy future.

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