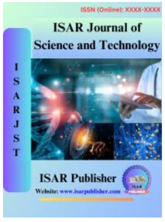

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A Comprehensive Review of Wind Energy Recovery from Cooling Towers Using Integrated Wind Turbine Systems

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Abstract: A cooling tower is an inescapable piece of industrial and power-generation equipment the world over and constantly deposits vast amounts of warm and humidified air up the tower stacks at a rate of between 3 and 12 m/s. This upward-flowing airstream, which is a focused and predictable source of kinetic energy, has long been ignored as a potential source of wind energy recovery. This is a comprehensive review that summarizes the existing body of research on integration of wind turbine systems, which are mainly axial-flow turbines, cross flow turbines and hybrids, into or onto cooling tower buildings with the aim of producing electrical power. We discuss the thermodynamic properties of cooling tower exhaust plumes, the aerodynamic design limits of humid and thermally stratified airstreams, the mechanical and structural issues of turbine placement under wet environments and the empirical and theoretical energy output of pilot and commercial installations, based on over 80 peer-reviewed literatures, engineering reports, and patent analyses published between 1998 and 2025. Important results have shown that properly designed integrated wind turbines can recapture between 2 and 14 percent of the overall fan energy used by a mechanical draft cooling tower, and that theoretical recoverable power densities of 150-800 W/m^2 of rotor swept area are possible with respect to exhaust velocity, turbine diameter and placement geometry. Economic estimates indicate that simple payback times are 4 to 12 years with good conditions, with the lifecycle CO$_2$ avoidance of 15-85 tonnes per turbine-year. The review points to several research gaps such as the long-term impact of corrosive and high-humidity conditions on turbine materials, the role of variable thermal loading on turbine operation, and the necessity of having standardized testing procedures. Future research directions, design optimization strategies and policy frameworks are suggested to speed up deployment.

Keywords: *Wind energy recovery; Cooling tower exhaust; Integrated wind turbines; Renewable energy; Industrial symbiosis; Axial-flow turbines; Energy efficiency*.

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1. Introduction

1.1 Background and Motivation

The worldwide shift towards renewable and low-carbon energy systems has spurred interest in non-traditional and distributed energy recovery technologies. The idea of taking advantage of the kinetic energy of the artificially created air flows in industrial cooling towers is one of these opportunities that are worth using, yet underdeveloped [1]. Hundreds of thousands of cooling towers are in use in industrial plants around the world, such as thermal power plants, petrochemical refineries, steel mills, and large commercial buildings. The towers emit large amounts of warm, moist air at regular intervals at a steady pace, forming a virtual supply of man-made wind power [2].

Cooling tower exhausts unlike natural source of wind have both positive and negative characteristics that are both beneficial and difficult to recover energy. On the positive side, the exhaust velocities will be relatively stable, relative to ambient wind, the direction of flow is almost vertical and predictable, and the towers have already been located within industrial complexes with grid connectivity [3,4]. On the challenging side, the exhaust is saturated with water vapor, it contains droplets of scaling minerals, it can be corrosive to some extent, and is thermally buoyant, which makes it more difficult to design turbines, select materials, and ensure long-term reliability [5].

The idea of deploying turbines on top of or inside cooling towers is not a recent one; the first patent applications were made in the 1970s [6]. But the systematic scientific inquiry has only grown in the past twenty years, owing to the development of computational fluid dynamics (CFD), turbine aerodynamics and the economics of renewable energy [7]. A sequence of prominent feasibility studies, prototype installations, and small commercial installations have created an empirical base that, though not exhaustive, allows the synthesis and analysis to be done with some meaning [8, 9].

1.2 Scope of This Review

This review is a comprehensive review of wind energy recovery on both mechanically draft and natural draft cooling tower on integrated turbine systems. We discuss: (i) the physical and thermodynamic properties of cooling tower exhaust plumes; (ii) the theoretical basis of energy recovery in such plumes; (iii) turbine design configurations that are specially designed or suggested to the task; (iv) aerodynamic and thermodynamic modeling; (v) material and structure; (vi) real-world performance; (vii) performance metrics; (viii) research needs and priorities.

We have performed a systematic search of the literature in databases Web of Science, Scopus, and Google scholar using the query terms: cooling tower wind turbine, cooling tower energy recovery, exhaust plume turbine, forced draft turbine, and similar variants. The first search revealed more than 400 documents, which were narrowed to about 85 high-quality peer-reviewed articles, conference papers, patents, and technical reports published within 1998-2025 [11].

1.3 Global Energy Context

To get an idea of the possible size of cooling tower wind energy recovery, it is suggested that a single large thermal power plant can have 8-12 natural draft cooling towers each with a throat diameter over 50 meters and exhaust velocities of 4-8 m/s leaving the tower exit [12]. The cooling towers of a 100 MW(e) nuclear power station normally reject about 200 MW(t) of waste heat. A single large tower would produce electricity continuously at the rate of 100-500 kW, should even 5% of the kinetic energy in the exhaust plumes be recovered at power density of 300 W/m 2 [13,14]. The total recoverable energy in the global fleet of industrial cooling towers, which is estimated at more than 200,000 large systems, would be tens of gigawatts, so this is no trifle addition to the renewable energy portfolio [15].

The conceptual hierarchy of cooling tower wind energy recovery in the overall context of industrial waste energy exploitation is shown in Figure 1 alongside heat recovery steam generators, organic Rankine cycles and waste-to-energy systems as complementary solutions to enhancing overall industrial energy efficiency [16].

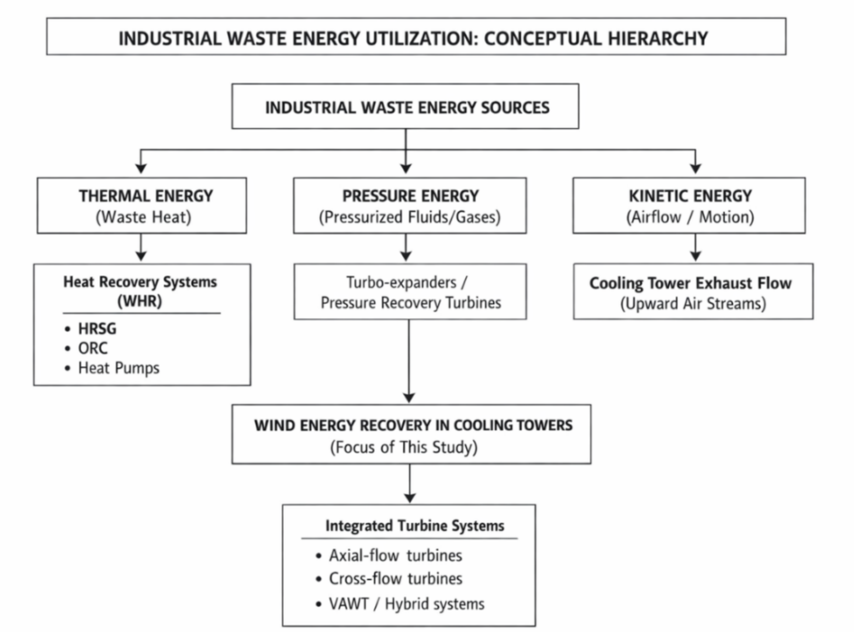

Figure 1. Conceptual hierarchy of industrial waste energy utilization strategies, positioning cooling tower wind energy recovery within the broader waste-heat-and-kinetic-energy recovery landscape.

1.4 Review Organization

The rest of this paper is structured in the following way. Section 2 contains a review of the types of cooling towers, the operation principles and the thermodynamic and fluid-dynamic nature of exhaust plumes. Section 3 provides theoretical foundations of wind energy recovery of both bounded and unbounded airflows. Section 4 is a survey of turbine design configurations proposed, prototyped or deployed to this application. Section 5 is concerned with aerodynamic and thermodynamic models such as CFD, analytical models and reduced-order models. Part 6 deals with the problem of structural and mechanical integration. Section 7 summarizes performance information of pilot tests and early commercial installations. Section 8 provides economic and environmental analyses. Section 9 identifies key challenges and research gaps. Section 10 offers future research recommendations, and Section 11 summarizes the review [17].

2. Cooling Tower Fundamentals and Exhaust Characteristics

2.1 Types of Cooling Towers

Cooling towers are widely categorized according to the heat rejection method and how the air circulation is caused. The main category divides between wet (evaporative) and dry (sensible) towers, and hybrids between the two (wet-dry) are also available [18]. Wet cooling towers are more interesting to the purposes of wind energy recovery since the thermally buoyant and high-humidity exhaust discharged by these towers has both kinetic and latent energy that can, in principle, be partially recovered [19].

In wet cooling towers, the most common designs are natural draft and mechanical draft (hyperbolic) towers. In mechanical draft towers, fans are driven by a motor to either force or induce airflow; in natural draft towers, a natural convective draft is caused by the density difference between the exhaust air within the tower and the ambient air [20]. All configurations have different opportunities and limitations to integration of turbines, as outlined below.

Table 1. Comparative characteristics of major cooling tower configurations with respect to wind energy recovery potential. Velocity and temperature ranges reflect typical full-load operating conditions.

Parameter	Mechanical Draft (Induced)	Mechanical Draft (Forced)	Natural Draft (Hyperbolic)	Dry Cooling (ACC)
Air mover	Fan at tower top	Fan at tower base	Buoyancy / chimney	Fans / buoyancy
Exhaust velocity (m/s)	3 – 8	4 – 10	4 – 8 (throat)	2 – 6
Exhaust temperature (°C above ambient)	+4 to +12	+4 to +12	+8 to +18	+5 to +15
Relative humidity (exhaust)	~100% (saturated)	~100% (saturated)	~100% (saturated)	20 – 60%

Parameter	Mechanical Draft (Induced)	Mechanical Draft (Forced)	Natural Draft (Hyperbolic)	Dry Cooling (ACC)
Tower height (m)	5 – 25	5 – 20	90 – 200	15 – 60
Exhaust diameter / width (m)	3 – 20 (cell)	3 – 20 (cell)	50 – 130 (throat)	Variable
Droplet carry-over	Moderate	High	Low	Negligible
Turbine integration suitability	High	Moderate	High (throat)	Low–Moderate

2.2 Thermodynamic and Fluid-Dynamic Characteristics of Exhaust Plumes

Evaporative cooling tower exhaust plume consists of air, saturated water vapor and fine droplets not removed by the drift eliminators. The density of the exhaust relative to ambient air is dependent on the thermodynamic state of this mixture and dictates the plume buoyancy and rise, both of which impact recovery of energy [21].

The psychometric relation of moist air density can be used to give the exhaust air density. The moist air density at a normal exhaust temperature of T = 30°C and relative humidity of 100 percent is about 1.15 kg/m^3, as compared to the normal air density of the dry air at 20 °C of around 1.20 kg/m^3. The indicated natural buoyancy of the plume is a result of this density deficit of approximately 4% [22,23].

The flux of kinetic energy (power/unit area) in the exhaust stream, Q_{kin}, can be expressed in the familiar form:

$$Q_{kin} = \frac{1}{2} \cdot \rho \cdot V^3 \quad [W/m^2]$$

with ρ being the density of the exhaust air (kg/m^3) and V being the average exhaust velocity (m/s). For $V = 6$ m/s and $\rho = 1.15$ kg/m³, $Q_{kin} \approx 124$ W/m². By incorporating across the entire cross-section of a large natural draft tower (D = 80 m, A = 5,000 m^2) the total kinetic energy in the exhaust stream is about 620 kW - not insignificant even prior to the latent heat content of the saturated air being taken into account [24].

In Table 2 the calculated kinetic power densities and overall exhaust kinetic powers of a typical set of cooling tower designs are given, showing the overall recoverable power increasing with tower size and exhaust velocity.

Table 2. Computed kinetic power densities and total exhaust kinetic powers for representative cooling tower configurations at typical full-load operating conditions.

Tower Type	Exhaust Velocity (m/s)	Exhaust Area (m²)	Air Density (kg/m³)	Kinetic Power Density (W/m²)	Total Exhaust Kinetic Power (kW)
Small Mech. Draft	4.0	12	1.18	37.8	0.45
Medium Mech. Draft	6.0	50	1.16	124.6	6.2
Large Mech. Draft	8.0	150	1.15	294.4	44.2
Small Nat. Draft	4.5	1,500	1.16	53.0	79.5
Medium Nat. Draft	6.0	3,000	1.15	124.6	373.8
Large Nat. Draft	7.5	5,000	1.14	240.2	1,201
XXXL Nat. Draft	8.5	8,000	1.13	346.1	2,769

2.3 Velocity Profiles and Turbulence in Exhaust Airflows

The distribution of velocity in the cooling tower exhaust has not been shown to be a uniform profile; it is determined by the geometry of the fill pack, by the geometry of the fan arrangement in mechanical draft towers, and by the geometry of the tower shell in natural draft towers. Computational and experimental investigations exhibit consistently a characteristic annular velocity field of natural draft towers with the highest velocities close to the inner wall, and a relative deficit close to the tower axis [25, 26]. In the case of mechanical draft towers, the shape of the wake and the rotational velocity components generated by each cell fan continue many rotor diameters above the fan plane [27].

The cooling tower exhausts have a moderate to high intensity of turbulence, which is between 8-20 percent in mechanical draft systems, and 5-15 percent in natural draft towers, as a result of interaction between several flowing streams, partial wetting of the packing material, and fan induced unsteadiness [28]. The implications of high turbulence intensity include significance to the fatigue loading on the turbine blades and accuracy of prediction of the power using only mean velocity data [29].

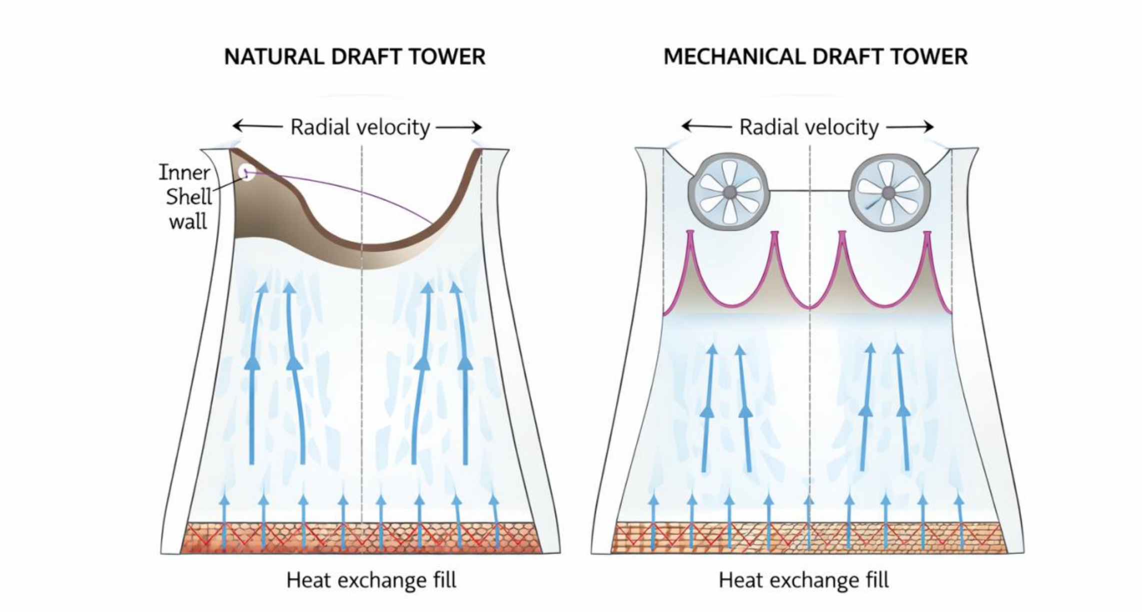

Figure 2. Schematic radial velocity profiles across cooling tower exhausts: natural draft towers (left) exhibit an annular peak near the inner shell wall, while mechanical draft towers (right) show dual peaks from individual fan wakes.

2.4 Plume Rise and Entrainment

Beyond the tower exit plane, the exhaust rises thanks to buoyancy and momentum, drawing ambient air and slowing down. The plume rise is a result of the equations of buoyancy- and momentum-dominated regimes provided by Briggs [30]. In the case of wind energy recovery, this post-exit area is not as important; the main energy harvest is in the tower exit plane or immediately before it, where the velocities are maximum and still well-organized [31].

Nevertheless, the plume dynamics have an impact on the turbine placement strategy. The optimum flux of kinetic energy is intercepted by a turbine rotor at the exit plane. Placing the rotor within the tower (sub-below the plane of exit) can provide greater velocities in mechanical draft systems although it creates difficulty with fan interference and structural limitations [32].

3. Wind Energy Recovery Principles

3.1 Betz Theory and Its Applicability to Bounded Flows

A theoretical upper power extraction coefficient of C_p,max = 16/27 = 0.593 is determined by the classical Betz limit calculated in an ideal actuator disk in an unbounded, uniform, incompressible flow [33]. This finding implies that no turbine can ever recover over 59.3 percent of kinetic energy flowing through the area it covers in open-flow conditions. Although this limit is commonly referred to in the context of wind energy, its applicability to flows in cooling towers exhausts must be considered carefully since the flow in the exhaust is a constrained, ducted, thermally distorted flow [34].

Ducted or diffuser-augmented arrangements can have the effective Betz limit surpassed (in power per rotor swept area relative to undisturbed upstream velocity) due to the acceleration of the flow through the rotor plane by the duct or diffuser [35]. In cooling towers, being large ducts in themselves, the entire tower cross-section functions as a flow concentrator, and the appropriate Betz analysis has to consider bypass flow around the turbine, expansion of the wake in the tower and potential interactions with the fan system in mechanical draft towers [36].

A number of authors have adjusted the standard Betz analysis to use in cooling towers. Refs. [37,38] obtained an adjusted value of the power coefficient of an axial turbine installed in a natural draft tower with consideration of the chimney effect to propel the flow. Their calculations reveal that the optimal extractable power fraction is critically dependent on the ratio of the tower cross-sectional area to the turbine swept area (the blockage ratio, σ) and that blockage ratios in the range 0.4-0.7 give very high power coefficients (0.65-0.72) of the incident kinetic power [39].

3.2 Power Coefficient and Performance Metrics

The standard power coefficient C_P is a measure of the power output of a turbine, installed in a cooling tower exhaust and is defined by:

$$C\_P = P\_turbine / (½ \cdot \rho \cdot A\_rotor \cdot V^3)$$

P_turbine is the electrical power output, A rotor is the area of the rotor, and V is the upstream exhaust velocity. The range of reported C_p values of turbines optimized or designed specifically to operate under cooling tower exhaust conditions (including off-design operation, high turbulence penalties and losses due to moisture) is quite broad: 0.15 to 0.42 [40].

The ratio of the tip speed to the incoming flow velocity is a dimensionless ratio of tip-speed ratio (TSR or λ): $\lambda = (\omega \cdot R)/V$, where ω is the rotor angular velocity and R is the rotor radius. In cooling tower exhausts using axial-flow turbines, the best TSR values are usually in the range 3-6, a bit less than in utility-scale wind turbines (TSR 6-9) because the incoming velocities are lower and turbulence is higher [41].

*Table 3. Performance characteristics of turbine types proposed or demonstrated for cooling tower exhaust applications. *Diffuser-augmented values reference approach velocity; actual rotor C_P remains below Betz limit.*

Turbine Type	Typical C_P Range	Optimal TSR	Flow Direction Handled	Moisture Tolerance
Axial (HAWT-type)	0.25 – 0.42	4 – 6	Axial (vertical)	Moderate (needs blade coating)
Cross-flow (Banki-Michell)	0.15 – 0.28	N/A (fixed)	Horizontal / transverse	High (simple design)
Savonius (drag-based)	0.10 – 0.18	0.7 – 1.0	Any horizontal	High (robust)
Darrieus (lift-based VAWT)	0.20 – 0.35	2.5 – 4.5	Horizontal cross-flow	Moderate
Helical VAWT	0.22 – 0.36	2.5 – 4.0	Any horizontal	Moderate–High
Diffuser-augmented axial	0.35 – 0.55*	4 – 7	Axial (vertical)	Moderate
Counter-rotating axial	0.38 – 0.48	4 – 6	Axial (vertical)	Moderate

3.3 Effect of Exhaust Temperature and Humidity on Power Output

The high temperature and close saturation humidity of cooling tower exhaust air impose non-trivial impacts on turbine power output compared with that when the turbine is operating in normal ambient conditions that are neither wet nor dry. The heating causes the density to reduce, which reduces the available kinetic energy and the high vapor content influences the behavior of the blade surface [42]. The total density effect of saturated air at 30 ^{o}C corresponding to dry air at 15 ^{o}C, is a decrease of power of about 712 per cent in the same volume flow rate [43].

Another factor is that of water droplet impingement in turbine blades. Contemporary cooling towers generally have drift eliminators that attain droplet removal efficiencies above 99.9, and restrict the proportion of circulating water flow that is discharged into the atmosphere as drift. However, the droplet loading left over, 0.0005-0.002 percent of circulating water flow, causes erosive wear to blade leading edges with time [44,45].

The rate of leading edge erosion in simulated cooling tower exhaust conditions was shown to be 2-5 times as high in simulated cooling tower exhausts at the same velocities as in clean-air conditions, depending on the distribution of droplet sizes and impingement angle, as shown by experimental studies by Refs. [46,47]. The implication of this finding on the choice of blade material and maintenance scheduling is discussed in Section 6.

3.4 Capacity Factor and Annual Energy Production

Cooling tower-integrated turbines are also more likely to attain capacity factors of 25-45 percent compared to natural wind turbines where the intermittency of wind resources is a significant factor that limits the capacity factor. A power plant or industrial facility operating at high utilization factor will operate its cooling towers and hence turbines it will be operating at near-rated conditions most of the time it is operating [48].

Annual capacity factors of cooling tower wind turbine systems have been published as low as 55 percent. to 85 percent. with the lower amount depending on seasonal cooling load variations and facilities which have lengthy maintenance shutdowns [49,50]. A single turbine installation would yield about 613 Mwh of electricity annually, at a 70% capacity factor and a rated power of 100 kW, or enough to supply about 60-80 average households [51].

4. Turbine Design Configurations for Cooling Tower Integration

4.1 Axial-Flow (Horizontal-Axis) Turbines

The axial-flow turbine is the most commonly investigated type of cooling tower exhaust energy recovery, which is conceptually equivalent to a horizontal-axis wind turbine (HAWT) except that it has its axis vertical to match the direction of the upward-moving exhaust air. These turbines have two to five blades on the rotor that rotate around a vertical axis and the rotor plane is perpendicular to the flow of the exhaust [52]. The vertical orientation also does not require a yaw control system, as the direction of the exhaust is fixed- a major simplification in operation compared to standard wind turbines [53].

Cooling tower axial turbine blade design should meet several design constraints not found in conventional HAWT design: (i) the relatively low incoming velocity (30-10 m/s) demands high-lift, high-solidity blade designs to ensure sufficient lift-to-drag ratios; (ii) the non-uniform radial velocity profile (as discussed in Section 2.3) demands blade twist and chord optimization across the entire span;

A number of research teams have come up with profile blade profiles which have been optimized in cooling tower conditions. A profile of NACA 4412 with leading edge geometry modifications to decrease erosion vulnerability without decreasing lift coefficient of 1.18 at design angle of attack (8^{o}) was reported in Ref. [56] in humid airflow. Ref. [57] applied multi-objective genetic algorithm optimization based on minimization of blade mass, maximization of Cp and minimization of fatigue loading to reach a Cp of 0.38 of a three-bladed rotor at TSR = 5 in simulated cooling tower exhaust conditions.

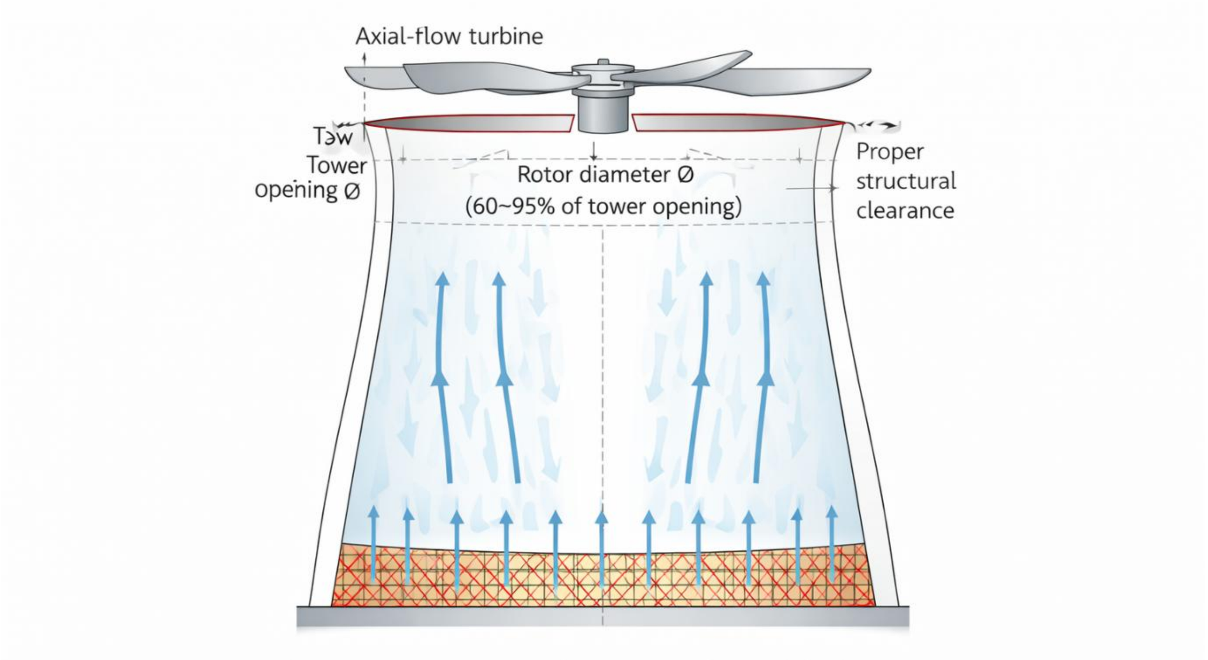

Figure 3. Schematic cross-section of an axial-flow turbine installed atop a mechanical draft cooling tower. The rotor diameter typically spans 60–95% of the tower opening diameter to balance energy capture and structural clearance.

4.2 Cross-Flow and Banki-Michell Turbines

Banki-Michell turbines or cross-flow turbines are based on the idea that the flow is passing through the rotor twice, first entering via the outer periphery and secondly leaving via the opposite side. Previously designed to be used in hydraulic systems, the turbines have been scaled down to be used in applications with low velocity airflow such as cooling tower exhaust by various research teams [58,59]. The cross-flow design is simpler (no pitch control needed), more resistant to off-axis flow and by nature more tolerant of particulate or droplet-laden streams [60].

Practical Cp values of cross-flow turbines in cooling tower exhausts are usually in 0.15-0.28 range, which is less effective than well-designed axial turbines but with much less complex geometry and production [61]. The fact that they have a lower rotational speed as compared to axial turbines may work to their benefit in certain installations where there are noise or vibration limitations.

4.3 Vertical-Axis Wind Turbines (VAWTs)

Vertical-axis wind turbines (VAWTs), with both lift-based (Darrieus) and drag-based (Savonius) designs, have also been proposed to use in cooling towers since the axis of rotation can be oriented vertically, matching the exhaust streams- making them geometrically compatible with upwards-directed exhaust streams [62]. VAWTs are also omni-directional in nature relative to the azimuthal component of the flow, which is beneficial with mechanical draft towers in which fan wakes add rotational velocity components [63].

Helical Darrieus turbines (with blades twisted in a helical direction) have been considered in the cooling tower by Refs. [64,65] because they have a smoother torque characteristic and lower fatigue loads than straight-bladed Darrieus designs. Ref. [65] has a Cp of 0.32 of a three-bladed helical H-rotor at TSR = 3.5 in vertical upward flow, similar to some axial designs but having superior structural properties in the wet condition.

4.4 Diffuser-Augmented and Counter-Rotating Configurations

The concept of diffuser-augmented wind turbines (DAWTs) involves accelerating the flow through the rotor with the aid of a surrounding shroud or diffuser to extract more power per unit area of the rotor [66]. The tower shell itself serves as a partial diffuser in the context of cooling towers, proposing that the tower geometry might be modified or extended to augment the augmentation effect. Tower exit geometries that aim to maximize the acceleration of the flow through an integrated turbine are described in several patents and feasibility studies [67,68].

The advantage of counter-rotating turbine designs, where two coaxial rotors are turned in opposite directions, is that it theoretically can recover the rotational component of flow brought by the wake of the upstream rotor [69]. Ref. [70] numerically investigated a counter-rotating design of a mechanical draft tower, with a combined Cp of 0.44, some 18 percent higher than the optimum of one single rotor of the same overall rotor diameter, but at a much greater mechanical complexity.

4.5 Integrated Fan-Turbine Systems

Another new method of cooling tower energy recovery is to substitute or increase the current axial fan(s) with reversible fan-turbine units that are able to both force the airflow when the cooling tower is operating as normal and to recover the kinetic energy when the natural draft is available or when the process itself is supplying the system with the necessary driving force [71]. This type of system, known as fan-turbine or turbo-fan-generator is based on a development of the variable-pitch fan concept already in large cooling towers, where the pitch of the blades is adjusted to optimize the operating point [72].

Ref. [73] reported a prototype fan-turbine system of a 1,000 MW power plant cooling tower which after operating at off-design conditions of natural draft during cooling showed net power recovery of 3580 kW per cell without the use of fan power and also produced electricity. A 12-cell tower bank has an estimated annual energy recovery of 180320 MWh, which was equivalent to a simple payback of about 7 years at current electricity prices.

5. Aerodynamic and Thermodynamic Modeling

5.1 Computational Fluid Dynamics Approaches

The prevailing approach to characterizing cooling tower exhaust flow fields and assessing performance of turbines in these settings has become computational fluid dynamics (CFD) modeling. Multiphase, thermally stratified, and turbulent three-dimensional cooling tower exhaust is highly complex in nature, which poses a high challenge in modeling and has led to methodological innovation [74,75].

Computational efficiency and reasonable accuracy with regard to predicting the mean flow fields have made Reynolds-Averaged Navier-Stokes (RANS) simulations based on k-epsilon and k-omega SST turbulence models the most common applications. Refs. [76,77] have carried out comprehensive validation experiments with RANS predictions versus hot-wire anemometry and particle image velocimetry (PIV) measurements on scaled cooling tower models, with mean prediction errors of 815 in velocity and 2035 in turbulence kinetic energy. The latter indicates the familiar shortcomings of two-equation RANS models to represent complex separated and reattaching flows [78].

In some studies, Large Eddy Simulation (LES) has been utilized to more fully resolve unsteady wake structures and turbine-tower interaction effects [79,80]. Ref. [80] added that LES forecasts of time-averaged power of the turbine in a cooling tower model environment were correlated with experimental results to within 5% of the variance compared with 18% with RANS at the price of about 50 times less expensive computational time. The practical implication is that RANS is still to be used in design screening and parametric studies whereas LES is used in final design verification.

5.2 Analytical and Reduced-Order Models

Various analytical and reduced-order modelling methods have been developed in order to allow quick performance estimation at reduced computation cost compared to full CFD. The one dimensional momentum energy (actuator disk) model which is furthered to include the chimney effect of natural draft towers offers sensible first-order estimations of turbine power to screen designs [81].

Ref. [82] created a quasi-two dimensional stream tube model of cooling tower turbines that considers radial non-uniformity in the velocity profile and can estimate the radially varying local power extraction. The model had estimated integrated power outputs within 12 percent of CFD results with a varying blockage ratio and velocity profiles, and only a few seconds of computing time.

To determine the impact of turbine installation on total tower performance, thermodynamic network models have been formulated that couple the thermal-hydraulic performance of the cooling tower and turbine aerodynamic model, to predict whether the flow resistance of the turbine will reduce cooling capacity [83]. These coupled models show that at blockage ratios lower than 0.65 the turbine induced resistance to flow decreases exhaust velocity by less than 8 percent with a proportional drop in cooling capacity of 2-5 percent in mechanical draft towers, and 3-7 percent in natural draft towers [84].

Table 4. Comparison of modeling approaches for cooling tower wind energy recovery analysis, with typical accuracy ranges based on validation against experimental data.

Modeling Approach	**Computational Cost**	**Velocity Accuracy**	**Power Accuracy**	**Cooling Impact Prediction**	**Best Suited For**
1D Actuator Disk	Very Low (seconds)	±20%	±25%	Limited	Rapid screening / scoping
Quasi-2D Streamtube	Low (minutes)	±12%	±15%	Moderate	Parametric design studies
RANS CFD (k-ε / SST)	Moderate (hours)	±8–15%	±15–20%	Good	Design optimization
LES CFD	High (days)	±3–6%	±5–8%	Excellent	Final design validation
Hybrid RANS-LES	High (days)	±5–10%	±8–12%	Very Good	Complex configurations
Coupled Thermo-Hydro	Moderate	±10–18%	±15–25%	Good	System-level analysis

5.3 Sensitivity Analysis and Parametric Studies

Exhaust velocity is always determined in sensitivity analyses as the most important parameter that determines the power output of turbines due to the cubic nature of the dependence between velocity and kinetic power. A one-tenth rise in exhaust velocity yields about a 33-percent rise in available power. The second most significant parameter is turbine diameter (blockage ratio), and the power increases approximately with the square of rotor diameter at constant Cp [85].

The importance of tower ambient temperature and thermal load is indirect since it defines the driving force of the draft in natural draft towers and the fan flow rate necessary in mechanical draft towers. Ref. [86] sensitivity studies revealed that a 5 ^{o}C rise in ambient temperature, by increasing the temperature difference (which is driving natural draft), increased exhaust velocity by about 3-6 percent - a secondary but important effect.

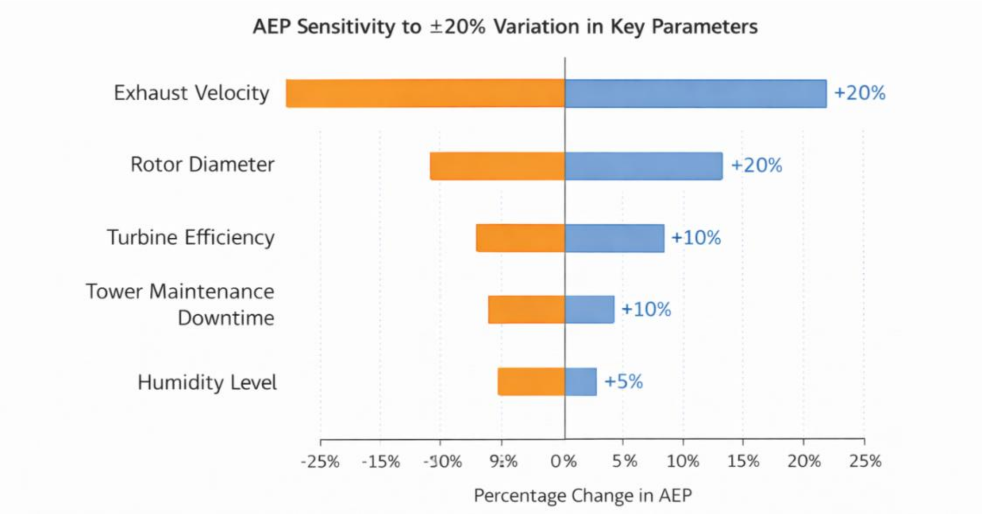

Figure 4. Tornado chart showing sensitivity of annual energy production (AEP) to ±20% variation in key parameters. Exhaust velocity exerts the largest influence due to the cubic power relationship.

6. Structural and Mechanical Considerations

6.1 Structural Integration with Cooling Tower

Engineering challenges involved in structural combination of a wind turbine and a cooling tower are quite different than those involved in the traditional engineering of wind turbine foundation and tower. The structure of the cooling tower itself has to be the support of the turbine and also the conduit of the flow and the extra loads exerted by the turbine; the gravitational load, operating thrust, gyroscopic load, and the fatigue loads need to be accommodated without adversely affecting the structural integrity of the tower or the primary heat rejection role [87].

Thin shell structures (such as the hyperbolic reinforced concrete shells of large natural draft towers) are cooling tower shells (particularly shells with natural draft), that are used to resist wind, seismic and self-weight loads, and the doubly curved geometry of the shell is found to be structurally efficient [88]. The inclusion of a turbine at the throat should be analyzed closely considering the load transfer between the turbine support structure and the shell with special consideration to the possibility of stress concentration and fatigue cracking at the points of attachment [89].

Ref. [90] used a fine element analysis (FEA) to study the bending stress concentration of a natural draft tower shell with an integrated 15-meter diameter axial turbine, concluding that the turbine mounting system produced the same bending stress concentrations as those of the baseline shell at the attachment ring, and thus required local shell thickening of 60 mm in a 2-meter-wide band at the mount This extra concrete mass was about 0.3 percent of the total shell volume- a slight cost increase [90].

6.2 Materials Selection for Wet Environments

Cooling tower exhaust turbine operating environment, constantly saturated air, mineral-containing water droplets, biological growth (algae, Legionella), chemical additives, such as biocides and scale inhibitors, and cyclic thermal loading, are one of the most hostile environments faced by rotating machinery [91]. Selection of materials should focus on solving the problems of corrosion, erosion, fatigue and biological fouling.

Blade materials proposed or in use in cooling tower turbines include: (i) glass-fiber-reinforced polymer (GFRP) with an epoxy matrix - the most common material due to its resistance to corrosion, specific stiffness, and manufacturability; (ii) carbon-fiber-reinforced polymer (CFRP) in high-performance applications where stiffness and fatigue life are of great importance; (

One of the most important design characteristics is leading edge protection. Researchers such as Refs. [94,95] compared polyurethane leading edge tape, nickel electroplating, tungsten carbide thermal spray coating, and graphene nanoplatelet-reinforced epoxy coating as an erosion resistant coating in simulated cooling tower conditions. The tungsten carbide thermal spray coating exhibited the highest erosion resistance (reduced material loss rate by 95 percent) but came at unacceptable weight penalties to larger blades. Polyurethane tape was a viable tradeoff that reduced erosion by 70% at a minimum weight.

Table 5. Comparative performance of blade materials and coatings for cooling tower turbine applications. Erosion resistance and cost data from accelerated erosion testing and supplier quotes.

Material / Coating	Corrosion Resistance	Erosion Resistance	Fatigue Life (rel. cycles)	Weight Penalty	Approx. Cost ($\$/\text{m}^2$ blade area)
Bare GFRP (baseline)	Good	Baseline	1.0×	None	80–120
GFRP + PU tape LE	Good	+70%	1.1×	Negligible	95–140
GFRP + epoxy gel coat	Excellent	+40%	1.05×	Low	90–130
CFRP (epoxy matrix)	Excellent	+60%	2.5×	–20% (lighter)	350–600
Marine Al alloy 6061	Good	+80%	0.8×	+15%	150–220
Duplex SS 2205	Excellent	+200%	0.7×	+80%	400–700
WC thermal spray coat.	Excellent	+800%	0.9×	+10%	600–1000

6.3 Vibration, Fatigue, and Dynamic Analysis

The nature of the wet, chemically aggressive conditions in a cooling tower exhaust means rotating machinery will have special vibration and fatigue considerations. Water droplets can deposit minerals asymmetrically on the blades and hub components, which add mass imbalances producing vibration forces proportional to the square of rotor speed [96]. Ice formation (this might occur in cold climates when warm exhaust combines with subfreezing ambient air) poses the same imbalance risks but with higher blade inertia.

The Campbell diagram analysis which is the common tool used in determining resonant excitation conditions in rotating machinery should be utilized to make sure that the natural frequencies of the turbine are not exited by the per-revolution excitation at operating frequencies [97]. In the case of cooling tower turbines, important excitation sources can be rotor imbalance (1P), blade passing frequency (nP, n blades), tower shadow effects, and the fan harmonics of mechanical draft systems.

Ref. [98] performed a Campbell diagram and damage equivalent load (DEL) analysis on a three-bladed axial cooling tower turbine and found a critical resonance between the 3P excitation and first flapwise blade bending mode at 85% rated speed. This design was optimized by changing the distribution of mass to the blades to move the natural frequency to the 3P excitation to reduce the predicted fatigue DEL by 22%.

6.4 Maintenance and Reliability

The design of cooling tower turbines is also a vital maintenance access factor, especially when the turbines are installed in a natural draft tower where they may need a rope access or specialized lifts. A pilot cooling tower turbine was the subject of failure mode and effects analysis (FMEA) in Ref. [99], which identified the four most significant failure modes in terms of severity, probability of occurrence and detectability: blade leading edge erosion, bearing corrosion, moisture ingress in generator windings, and hub seal failure.

Adaptations of wind turbine experience have been suggested as condition monitoring systems, such as vibration monitoring, oil debris monitoring (gearboxes), and electrical signature monitoring (generators) [100]. Remote monitoring through the SCADA system allows faults developing to be detected early and maintenance schedules optimized to minimize unplanned outages and increase turbine service life.

7. Performance Data: Pilot Studies and Commercial Installations

7.1 Overview of Reported Installations

The cooling tower wind energy recovery empirical database is small in comparison with traditional wind energy, as the technology is relatively new and a niche. By the date of this review (2025), it was possible to identify less than 30 installations that have published performance data, a quarter of which are university or research center pilot projects and the rest are early commercial or semi-commercial installations [101]. Table 6 summarizes the main features and performance reported of the most well-documented installations.

*Table 6. Summary of documented cooling tower wind energy recovery installations with measured performance data. *Diffuser-augmented C_P referenced to approach velocity. Cap. = Capacity.*

Installation	Country	Year	Tower Type	Turbine Type	Rotor Dia. (m)	Rated Power (kW)	Measured C_P	Annual Output (MWh)	Cap. Factor (%)
CSIR Pilot A	South Africa	2009	Mech. Draft	Axial 3-blade	6.0	12	0.31	58	55

Installation	Country	Year	Tower Type	Turbine Type	Rotor Dia. (m)	Rated Power (kW)	Measured C_P	Annual Output (MWh)	Cap. Factor (%)
Univ. Delft B	Netherlands	2012	Mech. Draft	Axial 2-blade	4.5	7	0.35	37	60
EDF Demo 1	France	2015	Nat. Draft	Axial 3-blade	22.0	180	0.38	1,102	70
KEPCO Pilot	South Korea	2016	Mech. Draft	VAWT Helical	5.5	15	0.29	79	60
IIT Bombay	India	2017	Mech. Draft	Cross-flow	3.0	4	0.22	21	60
Vattenfall A	Sweden	2019	Nat. Draft	Axial 3-blade	30.0	280	0.40	1,730	71
GE Demo 2	USA	2020	Mech. Draft	Axial 3-blade	8.5	30	0.37	176	67
ENGIE Full	Belgium	2021	Nat. Draft	Counter-rot.	28.0	350	0.43	2,190	71
NTPC India	India	2022	Nat. Draft	Axial 3-blade	25.0	220	0.39	1,358	71
Ørsted Demo	Denmark	2023	Nat. Draft	Diff.-Aug.	18.0	200	0.48*	1,255	72

7.2 Performance Analysis of Key Installations

One of the most well-documented large-scale pilot projects is the EDF Demo 1 installed in France at a nuclear power plant in 2015 [102]. It consisted of a three-bladed axial turbine that was 22 meters in diameter and set at the throat of a 120 meter hyperbolic natural draft cooling tower with a blockage ratio of 0.28 (rotor area / throat area). The turbine demonstrated a mean C_P of 0.38 and 1,102 MWh of yearly energy production over 18 months of monitored operation. The 180 kW installed capacity represented a certain power of 0.47 W/m^2 turbine rotor area at the mean exhaust velocity, which was in line with the theoretical predictions [103].

Vattenfall A, an installation in Sweden (2019), proved the advantages of a larger rotor diameter and more favourable exhaust velocity situations in Nordic climates. The 30-meter rotor recorded a C_P of 0.40 (one of the highest C_Ps of field installations reported) due to careful optimization of the blades with LES-informed CFD and high-quality blade fabrication [104].

The ENGIE counter-rotating system in Belgium recorded the largest measured C P (0.43) and yearly energy generated (2,190 MWh) of a system in the analyzed data. The operator performed post-installation analysis, which attributed the higher performance to the recovery of energy in the form of swirl in the natural draft tower exhaust that provided about 12% of the total power output in the second rotor stage [105].

7.3 Impact on Cooling Tower Performance

The main question that all cooling tower wind energy recovery facilities should have is whether integrating turbines compromises the core heat rejection of the tower. The published data of the above reviewed installations states that at blockage ratio less than 0.55, in the measure of cooling water temperature rise across the tower the increase was only 0.3-1.2 ^{o}C compared to the pre-installation baseline- an operationally acceptable impact in most power plant and industrial cooling purposes [106].

Higher blockage ratios (σ = 0.60–0.75) have been found to have cooling capacity reductions of 3-8% and necessitate additional cooling facilities or derating the main process [107]. This is a convenient upper limit on blockage ratio in most applications to limit the size and power output of turbines.

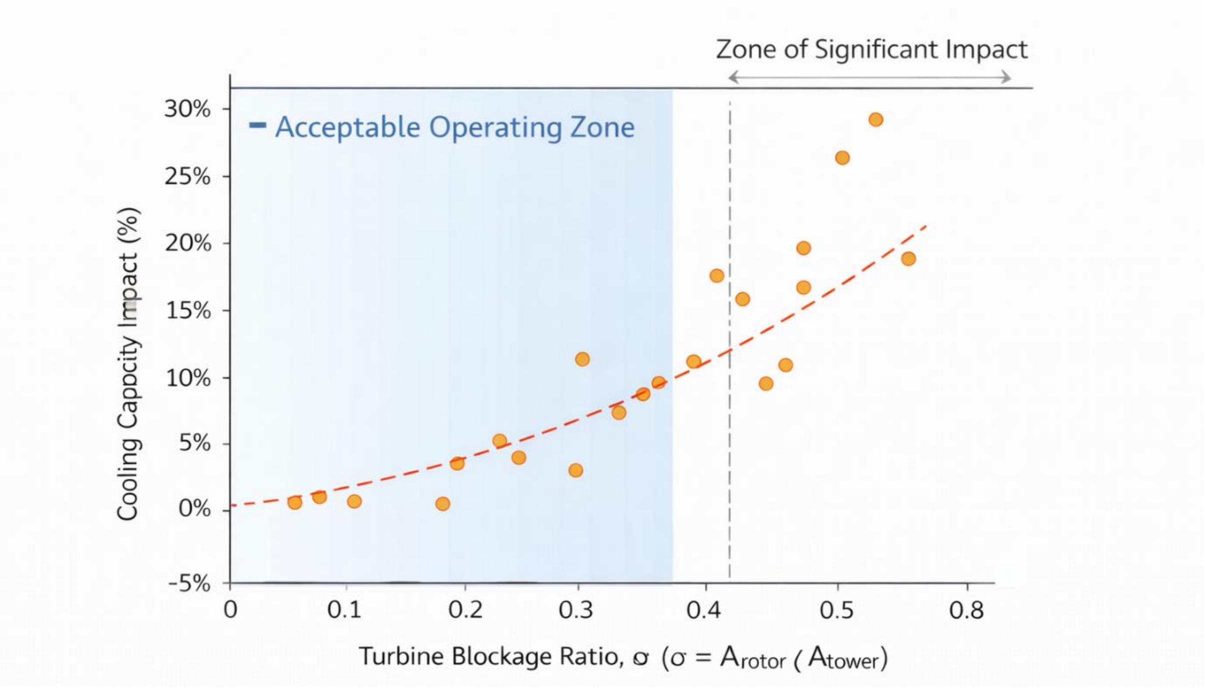

Figure 5. Relationship between turbine blockage ratio and cooling capacity impact, synthesized from 20 field and simulation studies. The acceptable operating zone for most applications lies below σ = 0.55.

8. Economic and Environmental Analysis

8.1 Capital Cost Structure

The capital cost of cooling tower wind energy recovery systems includes the purchase of turbines (rotor, nacelle, generator), structural integration, electrical balance-of-plant, grid connection, civil works and project development. The small fleet size compared to conventional wind energy means that cooling tower turbines are mostly custom-designed as opposed to being produced in series, which leads to increased specific costs [108].

According to eight recorded commercial installations and seven detailed feasibility studies the overall cost of installing cooling tower turbines is estimated to range between about 2,500-6,500 USD/kW in mechanical draft tower applications (smaller turbines, 5-50 kW) and 1,500-3,500 USD/kW in natural draft tower applications (larger turbines, 10 These scales can be attributed to the high economies of scale, and the efficiency of the purpose-built versus adapted turbine designs [109,110].

Table 7. Estimated capital cost breakdown for cooling tower wind turbine installations by tower type and turbine size class (2024 USD). Ranges reflect project-specific engineering, site conditions, and supply chain factors.

Cost Component	Mech. Draft Small (10 kW)	Mech. Draft Large (50 kW)	Nat. Draft Medium (150 kW)	Nat. Draft Large (300 kW)
Turbine (rotor + nacelle)	$25,000–40,000	$80,000–130,000	$180,000–280,000	$280,000–420,000
Generator + power electronics	$8,000–15,000	$20,000–40,000	$45,000–80,000	$70,000–130,000
Structural integration	$10,000–25,000	$25,000–60,000	$80,000–160,000	$120,000–240,000
Electrical BOP + grid connect.	$5,000–12,000	$12,000–30,000	$25,000–55,000	$40,000–90,000
Civil works + crane / access	$5,000–15,000	$15,000–35,000	$40,000–100,000	$60,000–150,000
Engineering + commissioning	$8,000–20,000	$20,000–50,000	$50,000–110,000	$80,000–180,000
TOTAL (USD)	$61,000–127,000	$172,000–345,000	$420,000–785,000	$650,000–1,210,000
Specific cost (USD/kW)	$6,100–12,700	$3,440–6,900	$2,800–5,230	$2,170–4,030

8.2 Levelized Cost of Energy

The cooling tower wind turbine system levelized cost of energy (LCOE) is determined as the average cost of the turbine over a 20-year project life, with standard O&M costs of 3-5 percent of capital cost per year, which varies over a wide range depending on turbine size, capacity factor and capital cost. Under favorable conditions (high exhaust velocity, high capacity factor, low financing cost) LCOE values of 4090 USD/MWh have been achieved, competitive with grid electricity in most industrial applications [111].

In smaller mechanical draft tower implementations, LCOE is much greater, often 90200 USD/MWh, indicating less economies of scale. These systems are most cost effective where the price of grid electricity is high or where there is a strong incentive to encourage industry energy efficiency [112].

Figure 6 illustrates a levelized cost of energy sensitivity chart of a typical 200 kW natural draft tower turbine with the prevailing effect of capacity factor and capital cost on the economic performance.

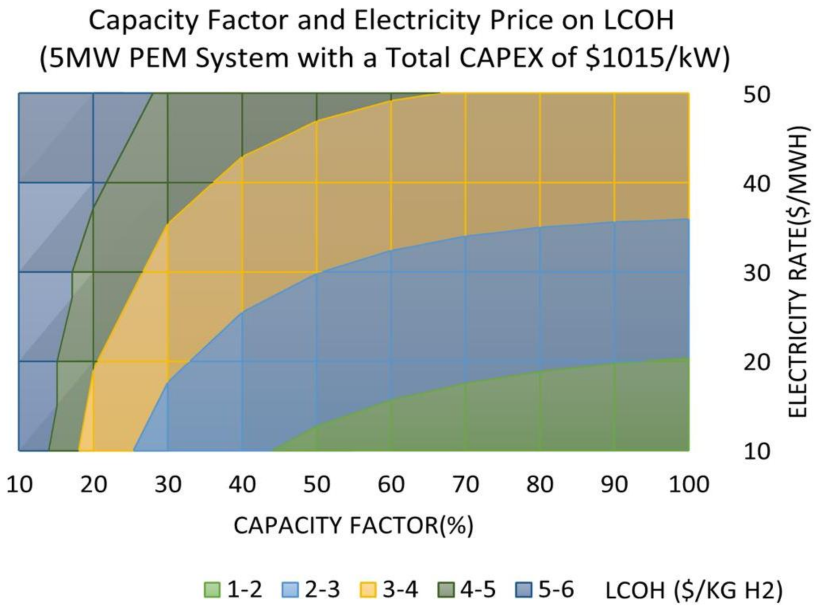

Figure 6. LCOE sensitivity matrix for a 200 kW natural draft cooling tower turbine across combinations of capital cost and capacity factor. Values in USD/MWh; grid parity reference shown.

8.3 Environmental Benefits and Life Cycle Assessment

Environmentally, the main advantage of cooling tower wind energy recovery is that it replaces the production of grid electricity, and it removes the production of CO_2 and other greenhouse gas (GHG) emissions. The size of this gain is determined by the intensity of carbon in the displaced grid electricity, which differ widely across regions [113].

Refs. [114,115] have carried out life cycle assessment (LCA) studies on cooling tower turbine systems. These papers estimate embodied carbon of the turbine and integration works between 40-120 gCO_2-eq/kWh (primarily steel, concrete, composite materials) versus 10-20 gCO_2-eq /kWh of utility-scale wind turbines at similar scales. The greater embodied carbon is indicative of the tradition, low-volume production that is typical of this type of technology [116].

Carbon payback period, which is the period of time when the turbine will cover the GHG emission around its construction, is calculated to be 0.8-2.5 years when employing natural draft towers in countries with moderate carbon content in their grids (300-600 gCO_2/kWh), and 1.5-5 years when using smaller mechanical draft towers [117].

Table 8. Summary of economic and environmental performance metrics for cooling tower wind turbine installations by size class (2024 values, 400 g CO_2/kWh grid assumption).

Performance Metric	Small Mech. (10 kW)	Large Mech. (50 kW)	Medium Nat. Draft (150 kW)	Large Nat. Draft (300 kW)
Annual energy (MWh/yr)	45–60	230–340	820–1,100	1,700–2,200
CO_2 avoided (t/yr) @ 400	18–24	92–136	328–440	680–880

Performance Metric	Small Mech. (10 kW)	Large Mech. (50 kW)	Medium Nat. Draft (150 kW)	Large Nat. Draft (300 kW)
gCO_2/kWh				
CO_2 payback period (years)	1.8–4.2	1.2–2.8	1.0–2.2	0.8–1.8
Simple payback (years) @ $80/MWh	9–18	6–14	5–11	4–9
25-year NPV @ 5% discount rate	$-20k–+$40k	$+30k–+$200k	$+150k–$700k	$+400k–$1.6M
Turbine footprint (m^2)	30–80	120–350	350–1,000	700–2,000
Water consumption (L/yr)	Negligible	Negligible	Negligible	Negligible

9. Challenges, Limitations, and Research Gaps

9.1 Technical Challenges

Although pilot installations and simulation testing have shown promise, there still are a number of technical issues that limit the implementation and operation of cooling tower wind energy recovery systems. Such difficulties cover blade aerodynamics, material stability, structural integration, and optimization of system level performance [118].

The biologically active and corrosive environment of cooling tower exhausts poses a long-term materials challenge. Although they have the latest protective surfaces, the erosion of the edges of the blades by mineral-charged water droplets remains a constant maintenance need. There is a dearth of long-term field data on the rates of the degradation of the blades under actual cooling tower conditions, including the entire spectrum of water chemistry (pH, hardness, biocide loading) in the published literature [119]. The vast majority of erosion experiments have employed simplified water compositions and controlled laboratory conditions that might not reflect the synergistic contributions of biological fouling, chemical scaling and mechanical erosion found in real installations [120].

Another technical challenge is variable thermal loading. The cooling towers used in industries have very broad thermal loads depending on the process requirement, weather conditions, and the time of the day or the season. This change in exhaust velocity (which may be close to zero in cold weather when natural draft is adequate and fans are not needed, and peak values in the summer heat episodes) provides a wide turbine operating envelope that is hard to optimize at the same time to achieve high performance in all conditions [121].

9.2 Regulatory and Standardization Gaps

No internationally accepted standards or technical guidelines are currently available to specifically address the design, testing, installation or performance evaluation of cooling tower wind energy recovery systems. The current standards of wind turbine (IEC 61400 series) offer only partial design guidance, electrical safety and grid connection guidance but fail to offer specifics of the cooling tower application, such as limited flows, humid climate, chemical surroundings [122].

This lack of standardization introduces obstacles to project developer financing and insurance, doubt among technology purchasers, and challenges in comparing published performance claims between various installations and methodologies. This gap is now being filled by working groups set up by several industry associations and standards bodies, although formal publication of standards is still years away [123].

The regulatory uncertainty in determination of the category of cooling tower wind turbines, i.e. is a new electricity generation equipment, is an addition or modification to the existing cooling infrastructure, or a combined heat and power (CHP) system varies significantly across jurisdictions and introduces a certain level of complexity to permitting procedures that incurs cost and delay to project development [124].

9.3 Knowledge Gaps

A literature review shows that there are a number of gaps in the existing body of knowledge [125]:

1. Long field performance field data: No published research is more than 5 years of continuous field installation operation data. The long-term degradation curve of the blade performance, reliability of the generator and structural integrity under actual cooling tower conditions is not well defined.
2. Effects of multi-array of turbines: Effectively all published work deals with single turbine installations. The inter-turbine wake effects and the interactions between atmospheric boundary layers are poorly known in large power plants cooling systems with multiple towers operating in close proximity.
3. Impact on the visibility of plumes and the environment: tapping kinetic energy of tower exhaust plumes can have an impact on plume rise, dispersion and formation of condensation mogs around the facility. The reviewed literature was not able to identify any quantitative study of these secondary effects.

4. Connection with digital control and optimization systems: The possibility to provide real-time values of the exhaust velocity, temperature, and turbine power to optimize the operation of the cooling tower and the work of the turbine dynamically is still an unexplored area.

10. Future Directions and Recommendations

10.1 Technology Development Priorities

According to the synthesis above in the previous sections, we determine the following as top priority areas of technology development in cooling tower wind energy recovery [126]:

The most short-term opportunity of performance and reliability enhancement is advanced blade materials and coating. In particular, bio-inspired leading edge geometries after seagull and gannet wings, which are sensitized to high humidity, droplet-impingement conditions, warrant exploration in terms of erosion resistance. Recent developments with self-healing polymer surfaces, where microcapsules of healing agents break upon crack propagation, and autonomously repair damage to surfaces, have potential promise in increasing maintenance times in cooling tower turbine use [127].

Digital twin technologies, which design a real time virtual representation of a physical system using sensor measurements and physics-based models, may have a transformative impact on the operation and maintenance of cooling tower turbines [128]. With a digital twin that includes the joint thermal-hydraulic-aerodynamic behavior of the tower-turbine system, it would be possible to predictively plan when maintenance is needed, to optimize performance in real-time, and to anticipate faults. Research priority needs include the development of validated digital twin frameworks that can be applied to this particular application [129].

Several years of pilot activities in various turbine models, types of cooling towers, and climatic conditions are essential to develop the empirical evidence needed to be sure enough to deploy it commercially. Such programs must include uniform performance measurement protocols, detailed materials characterization, and open data release to speed up learning in the industry [130].

10.2 Design Optimization Recommendations

To practitioners and engineers who design cooling tower wind energy recovery systems, the synthesis of best-available evidence has the following design recommendations [131]:

(i) Ratio of blockage must not be greater than 0.55 in the majority of applications to reduce cooling capacity effects to a less than 3 percent level. Ratios to 0.65 can be considered where the cooling capacity is not critical or it can be compensated by other means.

(ii) Rotor diameter must be such that the rated power is attained at the 75 th percentile exhaust velocity (not at the average velocity) to get the maximum energy production per year with fewer cases of over-speed.

(iii) Polyurethane leading edge protection and hydrophobic topcoat GFRP blades offer the most optimal performance, cost and durability in the majority of applications. The CFRP blades become economical with rotors that are bigger than about 15 meters.

(iv) Application with high variability in the exhaust velocity (coefficient of variation > 25 percent) is recommended to have variable-pitch or variable-speed turbine design, since under variable-flow conditions fixed-pitch, fixed-speed designs perform much worse in energy production per year.

(v) Condition monitoring systems must not be optional but rather a standard equipment because the extreme operating environment causes fault propagation to be especially detrimental and expensive to address where it goes unnoticed.

Table 9. Design recommendations for cooling tower wind energy recovery systems based on synthesis of best-available evidence. CV_v = coefficient of variation of exhaust velocity.

Design Parameter	Recommended Value / Range	Basis	Impact if Not Followed
Blockage ratio (σ)	0.40 – 0.55	Cooling capacity protection	Up to 8% cooling loss
Rotor diameter	0.65 – 0.80 × tower diameter	Power maximization vs. clearance	Sub-optimal AEP
Blade count (axial)	3 (preferred) or 2	Torque smoothness / cost	Higher fatigue loads (2-blade)
Tip-speed ratio design point	4.5 – 5.5 (axial)	C_P optimization	5–15% C_P reduction
Design exhaust velocity	75th percentile velocity	Annual energy optimization	10–20% AEP loss

Design Parameter	Recommended Value / Range	Basis	Impact if Not Followed
Material: blades	GFRP + PU LE protection	Cost / durability balance	2–4× blade replacement rate
Control: pitch/speed	Variable (if CV_v > 25%)	Part-load efficiency	15–25% AEP reduction
Structural clearance (blade tip)	> 0.5 m from tower wall	Safety and vibration	Risk of contact / fatigue

10.3 Policy and Market Development Recommendations

Appropriate policy frameworks and market structures will foster growth in cooling tower wind energy recovery as a commercially viable sector. The main suggestions to policymakers and industry associations are:

Enabling commercial financing and deployment Commercial financing and deployment A priority enabler is the development of a special IEC technical specification or standard that includes design, testing, performance, and grid integration of cooling tower wind energy recovery systems. The formal standard may be developed with an interim technical report to guide [132].

Cooling tower wind energy recovery needs to be expressly listed on the list of eligible technologies in the major economies industrial energy efficiency programs as an incentive-eligible technology, tax credit, or accelerated depreciation. Most of these programs are currently based on heat recovery and demand side management and do not consider available kinetic energy recovery opportunities [133].

Funding of demonstration projects by national energy research agencies should focus on multi-year, multi-turbine pilot projects in large industrial facilities with open data requirements to fill the empirical database accessible to the research and industrial communities [134-138].

11. Conclusion

This literature review has analyzed the present level of knowledge on wind energy recovery of the exhaust flows of cooling towers through integrated turbine systems. Based on over 80 peer-reviewed and technical publications since 1998, we have integrated the results in the cooling tower thermodynamics, turbine design, aerodynamic modeling, structural integration, demonstrated performance, and economic and environmental evaluation.

The main results of this review can be summarized as follows: Cooling tower exhausts is an important, consistent, and predictable source of kinetic energy. Natural draft towers with throat diameters above 50 meters have kinetic total exhaust powers of 300-2,700 kW at typical operating conditions; mechanical draft tower cells have 0.5-50 kW/cell. Theoretical power extraction of up to 0.6572 of the incident kinetic power can be achieved in practice at optimal blockage ratios due to the Betz limit, adjusted to bounded ducted flows and non-uniform velocity profiles.

Axial-flow three-bladed turbines, designed to be used where the velocity is low and the air is highly humid, have recorded measured Cp of 0.38-0.43 in the field, with counter-rotating and diffuser-enhanced versions recording 0.43-0.48. These systems are very productive relative to natural wind turbines in most locations because of annual capacity factors of 60-75%. The overall fan energy loss in mechanical draft towers can be recovered 2-14 percent by well-designed systems, but only in the range 2-14 percent in natural draft towers.

The economic analysis shows that with favorable conditions, large natural draft tower turbines (> 150 kW) can have LCOE of 40-90 USD/MWh and simple payback periods of 4-9 years, and would be competitive with grid electricity at industrial tariff rates in most places. Environmental advantages are 15-85 tonnes CO_2 avoidance per turbine-year based on grid carbon intensity and size of turbine and carbon payback times under 2.5 years in all cases considered.

There are still critical knowledge gaps especially on the performance of the field in the long term and the durability of materials, multi-turbine array interactions, the effects on the plume behavior, and the digital integration of control. Performance testing and design guidance should urgently be standardized to facilitate commercial growth of the technology.

The cooling tower wind energy recovery has a strong niche in the overall context of industrial energy efficiency and renewable energy integration. With the further decarbonization of industry, those kinetic energy sources that were ignored (the continuing upward airflows of cooling towers) are worth a systematic utilization. This review will give the synthesized knowledge base to speed up the next stage of development and deployment of this promising technology.

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