QATUAN
Biopiscinas & Ecopaisagismo

To:
From: Jamie Conway

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Wind Energy and the Pressure Economy:

A QAIB APPLICATION STUDY

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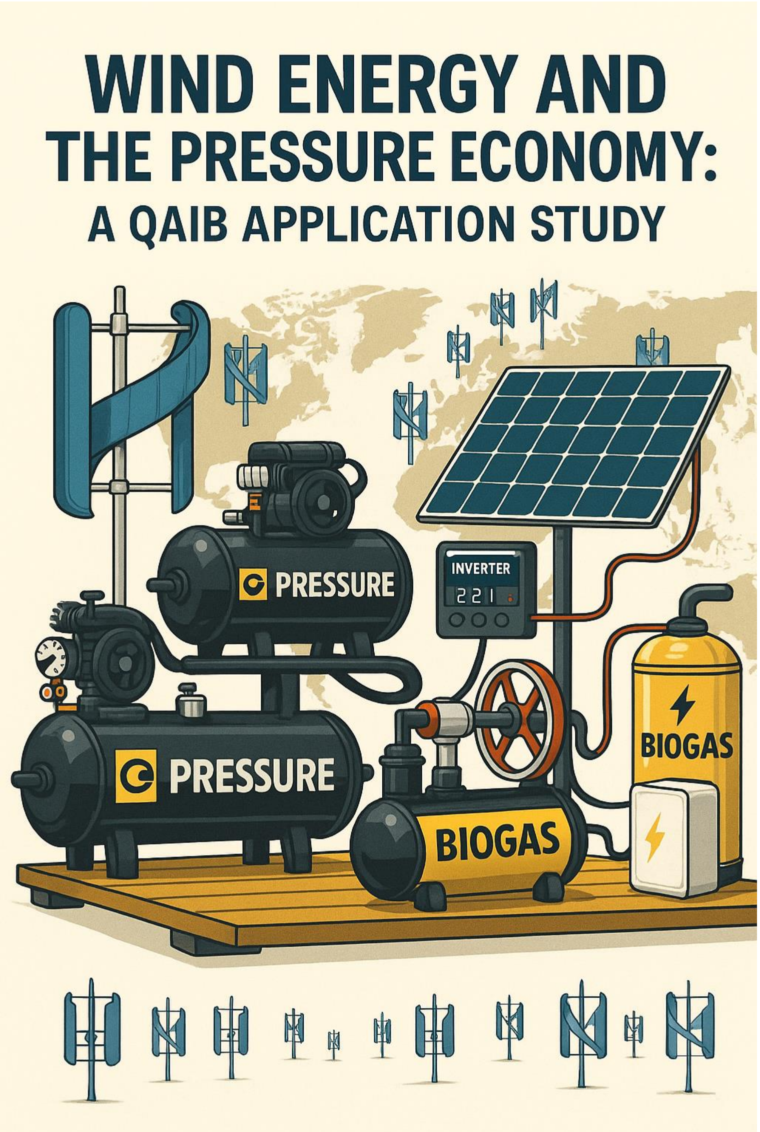

Abstract

This study presents the development and deployment of a modular, regenerative energy system powered by wind-driven pneumatic compression and solar photovoltaic support. Conducted through the Quantum Archaeoastronomy Institute of Brazil (QAIB), the project investigates the potential to eliminate the need for conventional battery storage by utilizing pneumatic air compression systems as an alternative, ensuring long-term sustainability and energy security.

Through field experimentation at Vila Qatuan (VQ) and theoretical alignment with advanced wind energy design tools, the research integrates meteorological analysis, turbine mechanics, micro-siting strategy, hybrid system design, and a four-phase deployment roadmap. The QAIB platform is positioned as both a viable alternative to diesel- or lithium-based systems and a pedagogical vehicle for open science, citizen engineering, and resilient community design.

The resulting "pressure economy" challenges conventional assumptions about storage, efficiency, and autonomy—proposing instead a distributed model rooted in mechanical intelligence, climate rhythm, and material reuse. Drawing upon ancient rotational logic and modern open-source innovation, the study culminates in a strategic framework for rural electrification and off-grid parity.

Figure 1: Satellite Location of Vila Qatuan

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Project Structure Overview

This report follows a modular framework paralleling course modules and real-world deployment stages—bridging technical design, data analysis, systems integration, and regenerative field application through the QAIB lens.

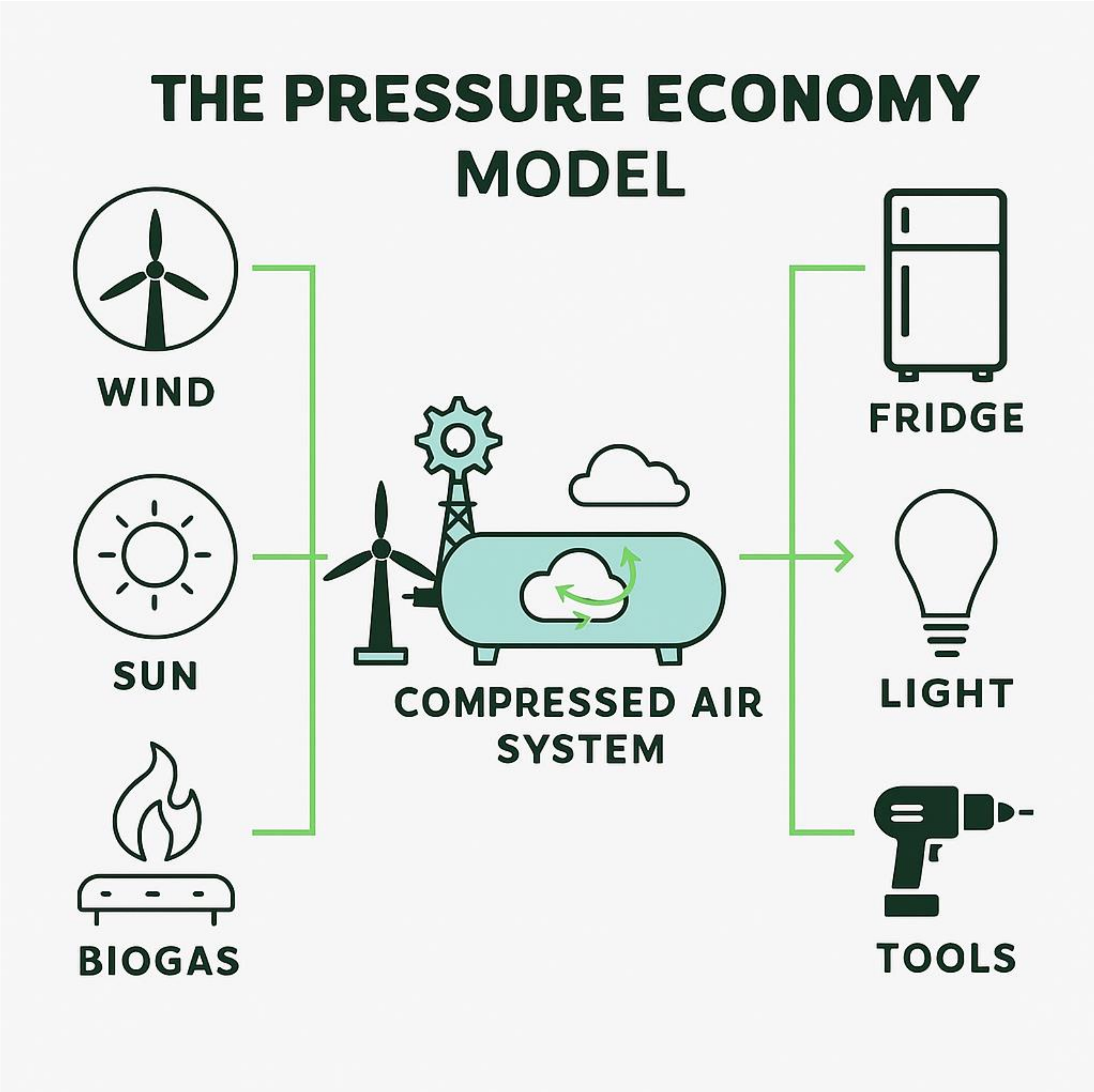


Figure 2: The Pressure Economy Model

A modular hybrid system harnessing wind, solar, and biogas to compress air as a renewable energy vector—powering essential off-grid needs like refrigeration, lighting, and tools without reliance on lithium or combustion.

Introduction

This study presents the development and deployment of a modular, regenerative energy system powered by wind-driven pneumatic compression and solar photovoltaic support. Conducted through the Quantum Archaeoastronomy Institute of Brazil (QAIB), the project explores the potential to eliminate the need for conventional battery storage by utilizing pneumatic air compression systems as an alternative, ensuring long-term sustainability and energy security.

Through field experimentation at Vila Qatuan (VQ) and theoretical alignment with advanced wind energy design tools, the research integrates meteorological analysis, turbine mechanics, micro-siting strategy, hybrid system design, and a four-phase deployment roadmap. The QAIB platform is positioned as both a viable alternative to diesel- or lithium-based systems and a pedagogical vehicle for open science, citizen engineering, and resilient community design.

The resulting **'pressure economy'** offers a paradigm shift by redefining energy storage, efficiency, and autonomy through pneumatic air compression. This innovative approach not only challenges conventional battery-based systems but also opens pathways for distributed energy systems that align with renewable and low-tech energy solutions. Drawing upon ancient rotational logic and modern open-source innovation, the study culminates in a strategic framework for rural electrification and off-grid parity.

1.1 Prototype Phase I: PV-Driven Pneumatic Battery

To begin validating the compressed air energy storage approach without requiring immediate windmill installation, QAIB will initiate a PV-powered prototype test at the reception site. This system leverages the underutilized capacity of an existing 3.6–4 kW PV array, originally installed for water pumping.

System Logic

- **Available Energy Window**: ~8 hours/day of solar availability
- **Pumping Load**: Only 1–2 hours used for water delivery
- **Surplus PV Time**: 6+ hours daily for pressure storage experiments

Objective

To test how long it takes to fully pressurize a 50 L air tank using existing PV, via a 2–3 HP compressor, and determine real-world energy recovery via compressed air discharge.

Stage I Kit (Estimated)

- Compressor (2–3 HP): R$1800
- Air Tank (50–100 L): R$800
- Fittings, Safety Valve, Gauge: R$350
- Basic Cooling/Drain Setup: R$200
- Monitoring (Optional): R$300
- Labor & Installation: R$500

Total Cost Estimate: R$3,950
Estimated Build Time: 4 hours

This low-risk, early-stage test provides critical operational insights before the construction of larger turbine masts or full pneumatic hybrid systems. It also establishes a learning and demonstration platform for QAIB's regenerative energy education program.

1.2 The Ionic Mill: Mechanizing the Transition from Current to Pressure

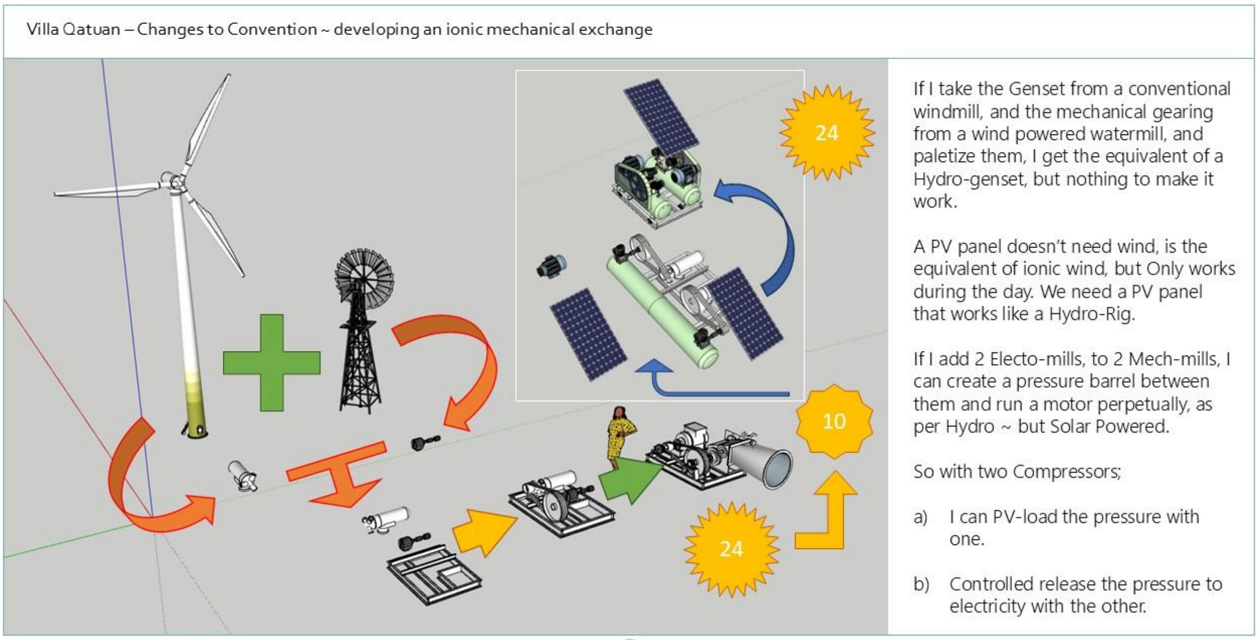


Figure 3: Process diagram showing conversion from electrical current to compressed-air mechanical drive using QAIB's hybrid infrastructure.

This system vision illustrates the union of wind and solar energy logic into a shared pressure-based reservoir. By abstracting the **genset** from a conventional windmill, and combining it with the **mechanical gearing** of a watermill, a hydro-like assembly is constructed without a fluid flow driver. Here, the **PV panel** operates not merely as a source of electricity, but as an **ionic input**—generating pressure through daylight hours that can be harnessed like a hydro-head through controlled discharge.

By coupling:

- Two **Electro-mills** (PV-powered compressors) with
- Two **Mech-mills** (air-powered generators),

...the system forms a closed-loop pressurized battery. One mill charges, the other discharges. A **barrel of compressed air** becomes a temporal converter—collecting solar flow during the day and yielding electric potential through mechanical means at night.

This is not just an energy model. It's a **conceptual reframing** of what wind, solar, and pressure represent: an **ionic exchange** across atmospheric layers. Wind becomes not mere motion, but an ion field drift—slow-moving, dense, breathable plasma. And with this model, QAIB enters the earliest stage of mechanical-plasma convergence.

1.3 Phase II Reflection: Toward Acoustic and Ionic Light

As we refine the pressure logic embedded in this system, a deeper realisation begins to emerge: this configuration is not just a mechanical emulator of hydro and wind—it **mirrors atmospheric light capture and waveform modulation.**

Like the Earth's atmosphere, our PV system absorbs solar energy and converts it into usable pressure. In doing so, it does more than replicate a hydraulic system—it initiates a **waveform**. The compressed air isn't merely a carrier of stored energy; it's a *medium of vibration*, tuneable like a string or pipe.

From here, the concept unfolds:

- Sound becomes a **byproduct of captured light**, stored in the oscillation of air.
- Directed air streams can be **shaped into infrasonic or ultrasonic waveforms**.
- These waveforms, moving through ambient air, have the potential to **interact with crystalline matter**—such as **quartz**.

Given quartz's piezoelectric nature, it may be possible to:

- Stimulate **pressure luminescence**, making the quartz glow
- Induce **electric microcharge** through acoustic impact alone
- Initiate **resonant feedback loops** through sonic cycling

This marks the beginning of a shift from *mechanical pressure systems* to **atmospheric plasma gateways**—where compressed air becomes a modulation tool, and sunlight becomes the original ionic charge.

This chapter closes with one eye on the **next field test**, and the other on the **phase horizon**: where light meets matter, and pressure becomes presence.

1.4 The Pyramid Model: Phase-State Engineering and the Ancient Blueprint

At its essence, the QAIB prototype is a **miniature pyramid**. It collects atmospheric flow. It organizes pressure within internal chambers. It radiates out its function based on geometry and timing.

Where the ancient pyramid harnessed thermal gradients, geologic resonance, and piezoelectric stone alignments to achieve unknown—but observable—effects, the QAIB system recreates the same model:

- A geometric base to collect energy (pallet)
- A central chamber (air tank) under pressure
- A solar apex (PV) that gathers and activates
- And sonic channels (valves and piping) that control discharge

Wind becomes light. Pressure becomes sound. Storage becomes frequency. And power, once chaotic, is now measured in **resonant intervals**.

As the ancients did with stone, we now do with air.

This marks a new chapter in energy thinking—not a rejection of science, but its **return to elemental logic.**

2. Physical and Meteorological Foundations (with EOLO Dataset Integration)

Wind is the result of differential heating of the Earth's surface by solar radiation, which induces pressure gradients due to uneven temperature distributions between equator and poles. These gradients drive large-scale atmospheric motion, further deflected by the Coriolis force arising from Earth's rotation. At smaller scales, wind is shaped by surface roughness and orographic features which influence turbulence, frictional drag, and local flow accelerations.

The structure of the atmosphere is stratified into the troposphere and stratosphere, with wind turbines typically operating within the atmospheric boundary layer (~100 m to 2 km above ground level), where wind speed and direction are heavily influenced by terrain and thermal gradients.

To estimate wind velocity at turbine hub height, we apply:

Power Law:

$$v(z) = v_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha}$$

Where:

- v(z)v(z)v(z): wind speed at height zzz
- vrefv_{ref}vref: wind speed at reference height zrefz_{ref}zref
- α\alphaα: shear exponent, terrain-dependent (e.g., 0.10 for sea, 0.25–0.40 for forests)

Logarithmic Law:

$$v(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right)$$

Where:

- u∗u_*u∗: friction velocity
- κ\kappaκ: von Kármán constant (~0.4)
- z0z_0z0: surface roughness length

Air density (ρ\rhoρ) affects kinetic energy capture. At 1200 m elevation (VQ), ρ≈1.06–1.08kg/m3, resulting in a ~12% loss in available energy relative to sea level. This demands larger rotor diameters or higher efficiency at low wind speeds.

Wind resources are commonly described using the **Weibull distribution**, characterised by:

- **A (scale parameter):** related to average wind speed
- **k (shape parameter):** describes spread (k > 2 = stable winds, k < 2 = variable)

These are derived from long-term data or short-term mast recordings adjusted with correction factors.

Turbulence Intensity (TI) is defined as:

$$TI = \frac{\sigma}{\bar{v}}$$

Where σ\sigmaσ is the standard deviation of wind speed, and v¯\bar{v}v¯ is the mean. TI impacts fatigue loading and determines turbine class (IEC 61400-1: Class I = high wind, Class III = low wind).

Measurement Standards:

- Anemometer at 10 m with data extrapolated to hub height
- 1-year+ recording preferred for investment-grade analysis

2.0 Track A: EOLO Site – Wind Profile and 100 m Analysis

Site Overview

Location: EOLO Wind Research Station (training dataset)
Hub Height: 100 m
Terrain: Flat coastal plain
Turbine Class: IEC Class 2
Measurement Period: Full year continuous logging

Figure 4: Regional overview of the EOLO test environment used for course wind simulations.

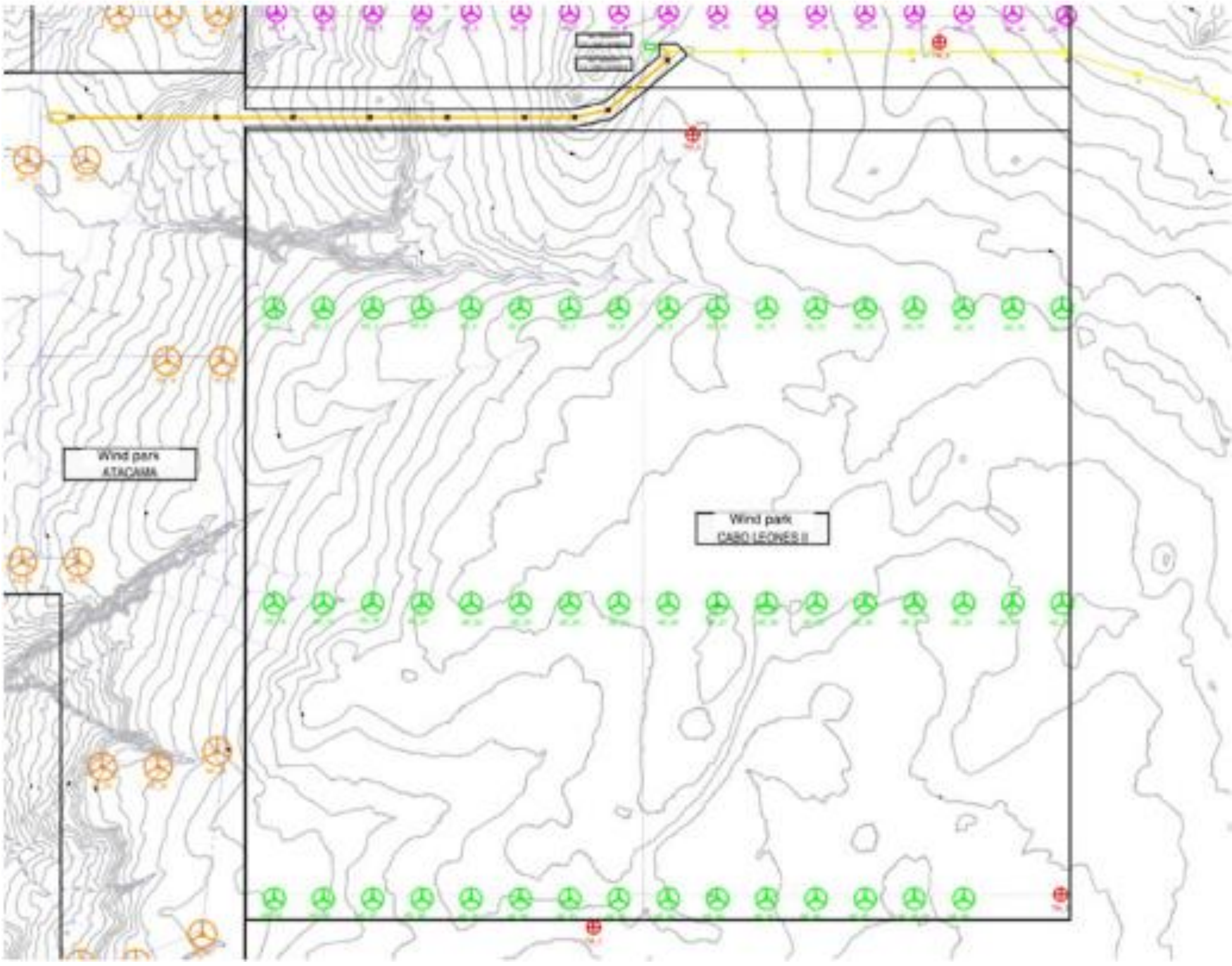


Figure 4: EOLO Wind Farm Site Layout and Turbine Placement
Topographic map showing turbine alignment across three rows spaced for optimal wake recovery. Layout follows flat coastal terrain contours to maximize exposure to prevailing NE winds and minimize construction grading.

Weibull Parameters – 100 m

- Shape factor (k): 1.64
- Scale factor (A): 9.03 m/s

Image: Weibull PDF – EOLO 100 m

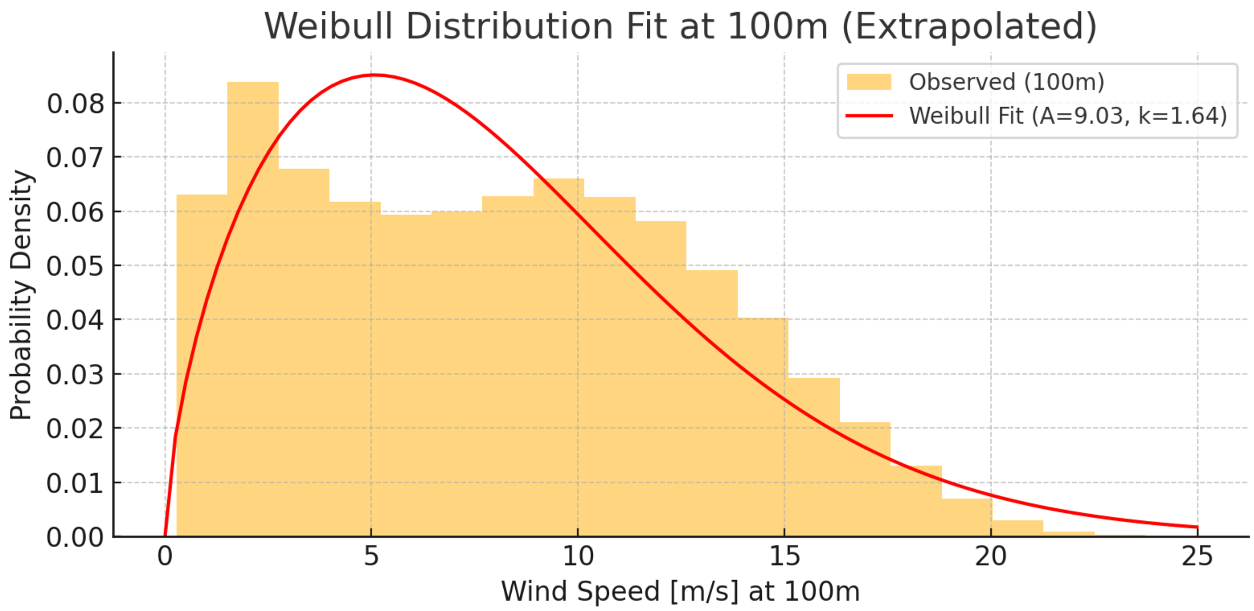


Figure 6: EOLO Site Weibull Distribution at 100m
Observed wind speed frequency and probability density fit using Weibull parameters A = 9.03 m/s and k = 1.64, extrapolated from mast data.

Accumulated Probability Curve – EOLO 100 m

- 50% exceedance: ~8.6 m/s
- 90% exceedance: ~5.4 m/s
- 25% exceedance: ~11.3 m/s

Cumulative Wind Speed Exceedance Curve – EOLO 100 m

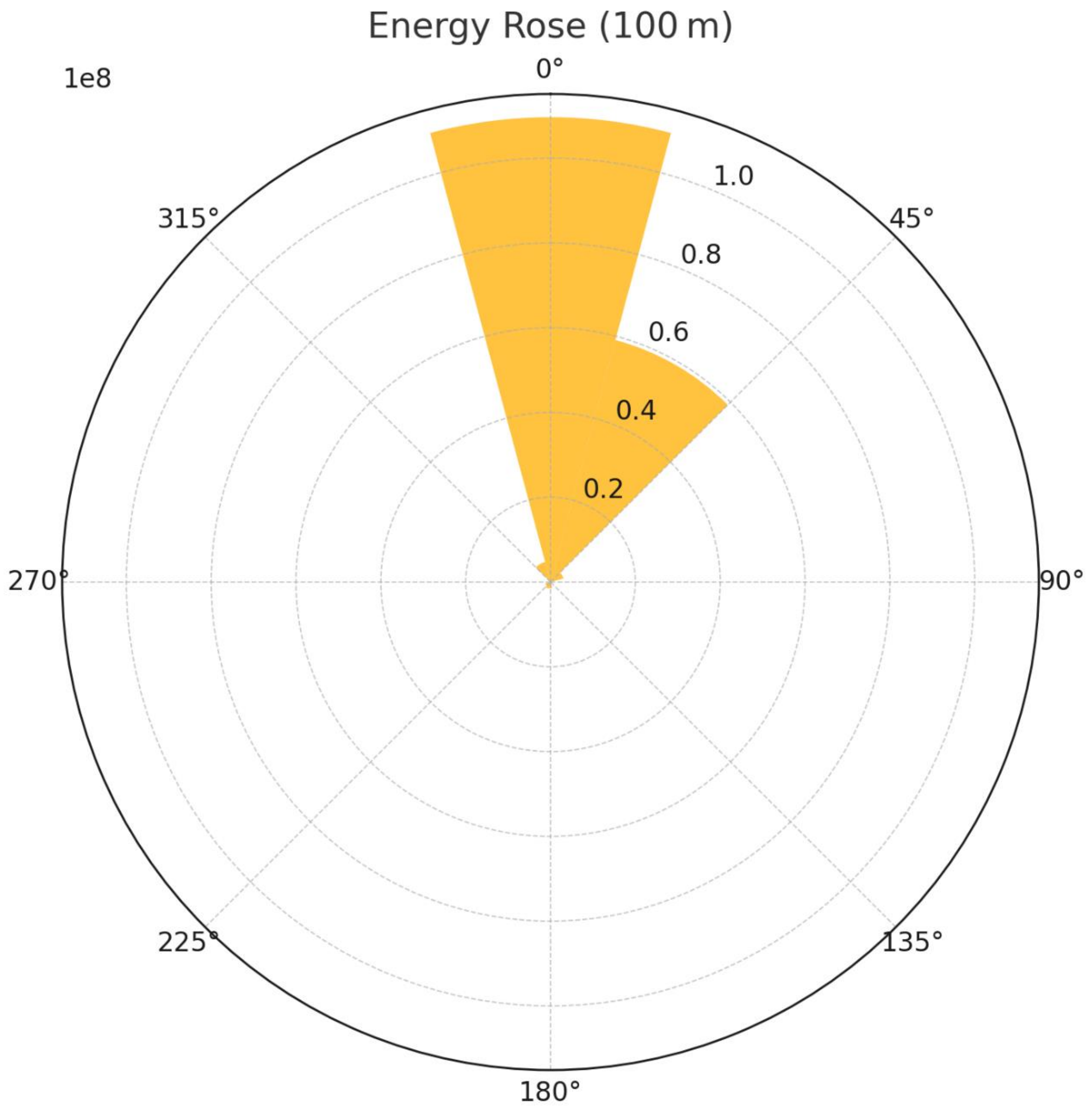


Figure 7: EOLO Site Energy Rose at 100m
Seasonal energy distribution profile showing dominant wind energy delivery from the NE sector. Data derived from EOLO mast logging at 100m elevation and aggregated into directional energy flux by sector.

Wind Roses – EOLO 100 m

Annual Wind Direction Profile:

- Predominantly from NE sector
- High-speed contributions from east and southeast directions

Frequency, Speed, and Energy Roses – EOLO 100 m

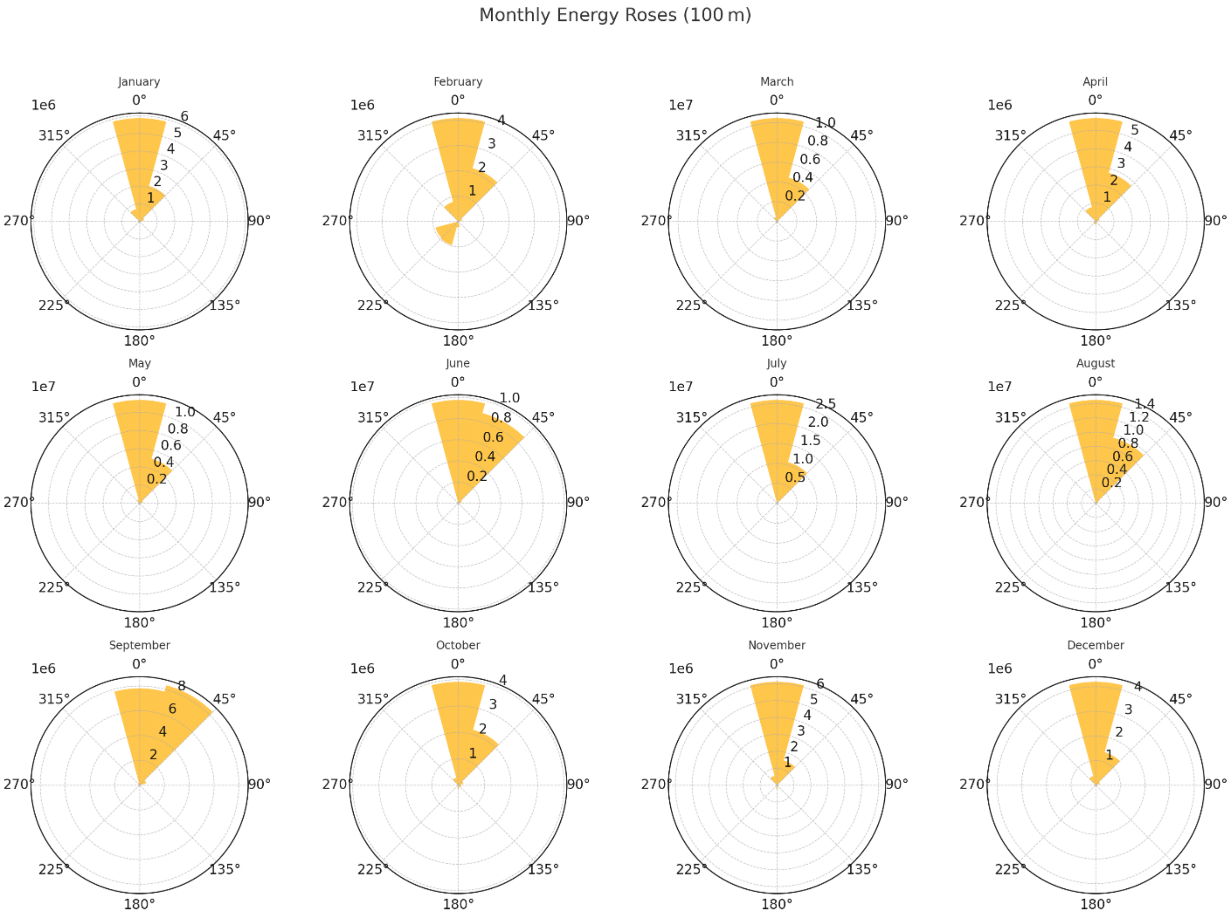


Figure 7: Monthly Energy Rose Diagrams (100m)
Twelve-month polar plots showing seasonal variation in wind energy delivery at 100m hub height. Data from EOLO mast logging highlights shifts in dominant inflow direction and energy intensity throughout the year.

Wind Speed Variation – EOLO 100 m

Daily Mean Wind Speed Plot

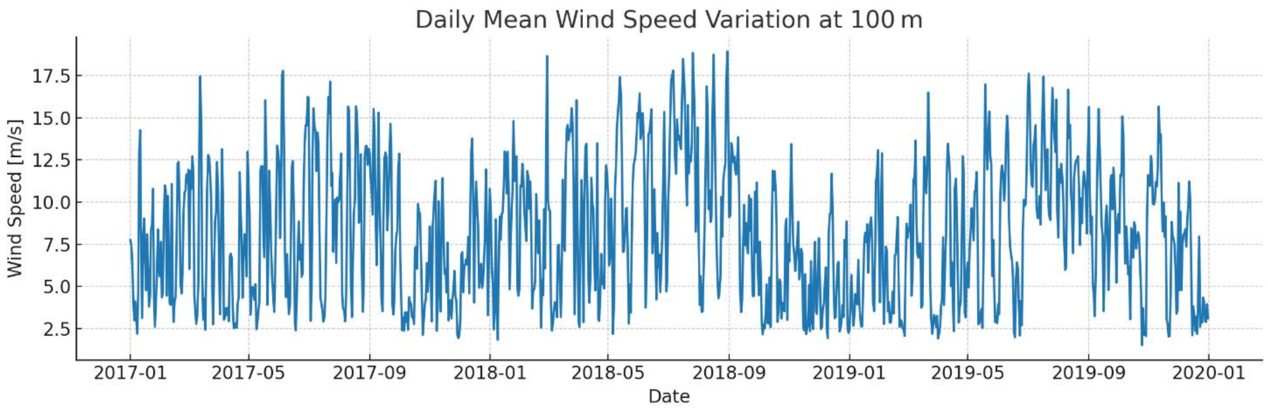


Figure 8: Annual variation of daily average wind speeds, highlighting reliability and troughs.

Monthly Summary Table – EOLO 100 m

Complete Monthly Wind Stats – EOLO

	Mean speed	Max speed	Min speed	Mode speed	Std speed	Wind speed 100m
January	6.932302375	21.26917972	0.278567961	1.757041623	3.995456472	7.8
February	7.172776916	24.98032401	0.317773823	4.405500723	4.170579574	8.07
March	8.301082494	22.84566803	0.275472762	2.344097809	5.01156925	9.31
April	6.744162348	19.9753863	0.275472762	1.008003327	4.594110336	7.48
May	8.559247608	23.86192523	0.275472762	1.165858505	5.077386878	9.61
June	9.042519587	22.54233848	0.275472762	1.005939861	5.250280743	10.17
July	12.24297647	24.89675362	0.278567961	15.69678876	5.206238995	13.79
August	10.13424988	24.17763558	0.283726627	10.23995191	5.189421596	11.44
September	9.231189161	24.40255342	0.298170892	11.49763467	4.444148802	10.42
October	6.010204564	18.97976377	0.275472762	1.285539555	3.930307032	6.7
November	6.757721361	22.96019042	0.278567961	3.933998655	4.072485591	7.58
December	6.010121718	18.67333901	0.295075692	1.754978157	3.526261015	6.76

Figure 9: Summary Statistics of monthly average wind speeds, highlighting reliability and troughs.

Extreme Wind Event – EOLO (50-Year Return)

- Reference Wind Speed (Vref): 28.83 m/s
- Application: IEC turbine classification and structural design limit

Wind Speed Percentiles

- P99: 19.28 m/s
- P90: 14.88 m/s
- P75: 11.81 m/s
- P25: 3.74 m/s

Turbulence and Shear

- Turbulence Intensity (TI): 0.607 (High)
- Shear Coefficient (α): 0.14 (open flat terrain)

2.1 Track B: Wind Profile and Siting at Vila Qatuan (Hub Height: 18 m)

Site Overview and Siting Rationale

Location: Vila Qatuan (VQ), central Brazil
Coordinates: 13°49′34.20″ S, 47°26′26.38″ W
Elevation: 795 m
Vegetation height: 5 m (average tree height)
Windmill mast height (target): 18 m (10 m clearance above vegetation)
Siting aligned: with IEC 61400 recommendations for Class III turbines

VQ's energy lab is situated atop a gently rising hill with a 15 m gain over approximately 100 linear meters. Prevailing ESE winds are captured from open terrain with minimal upstream obstruction. To comply with IEC turbine siting standards (minimum 10 m clearance above any obstacle within 100 m radius), the optimal hub height is set at 18 m.

VQ Site Mast Geometry and Tree Line Exposure

Figure 10: VQ Wind Farm Site Layout and Turbine Placement
Hilltop siting logic for 18 m mast clearance above vegetation canopy.

Weibull Parameters (Estimated at 18 m)

Using GWA dataset interpolation and power law adjustment from 100 m profiles:

- Shape factor (k): 1.59
- Scale factor (A): 7.6 m/s

The wind profile at 18 m confirms consistent energy availability for low-speed turbines such as Savonius rotors, tuned for mechanical torque.

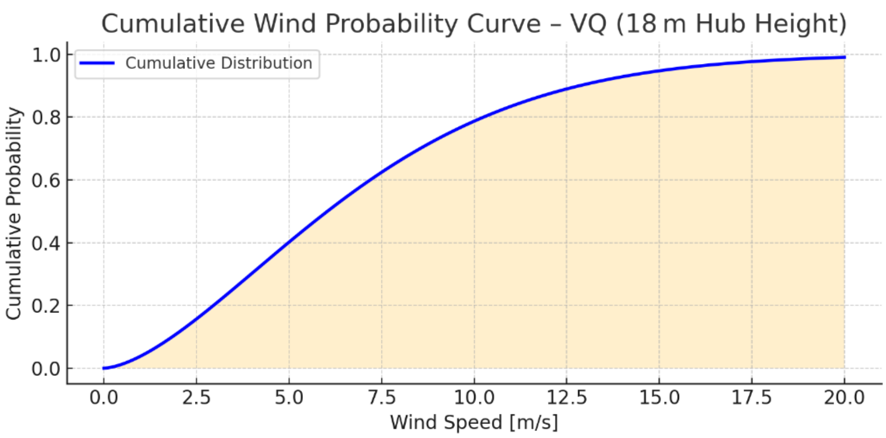


Figure 11: Probability distribution of wind speeds at hub height based on power law-adjusted interpolation from 100m profiles.

Accumulated Probability Curve – VQ 18 m

Using fitted Weibull parameters, we calculate the cumulative wind speed exceedance:

- 50% exceedance: 7.2 m/s
- 90% exceedance: 4.2 m/s
- 25% exceedance: 9.6 m/s

This informs turbine start-up speed analysis, torque optimization, and mechanical clutch design.

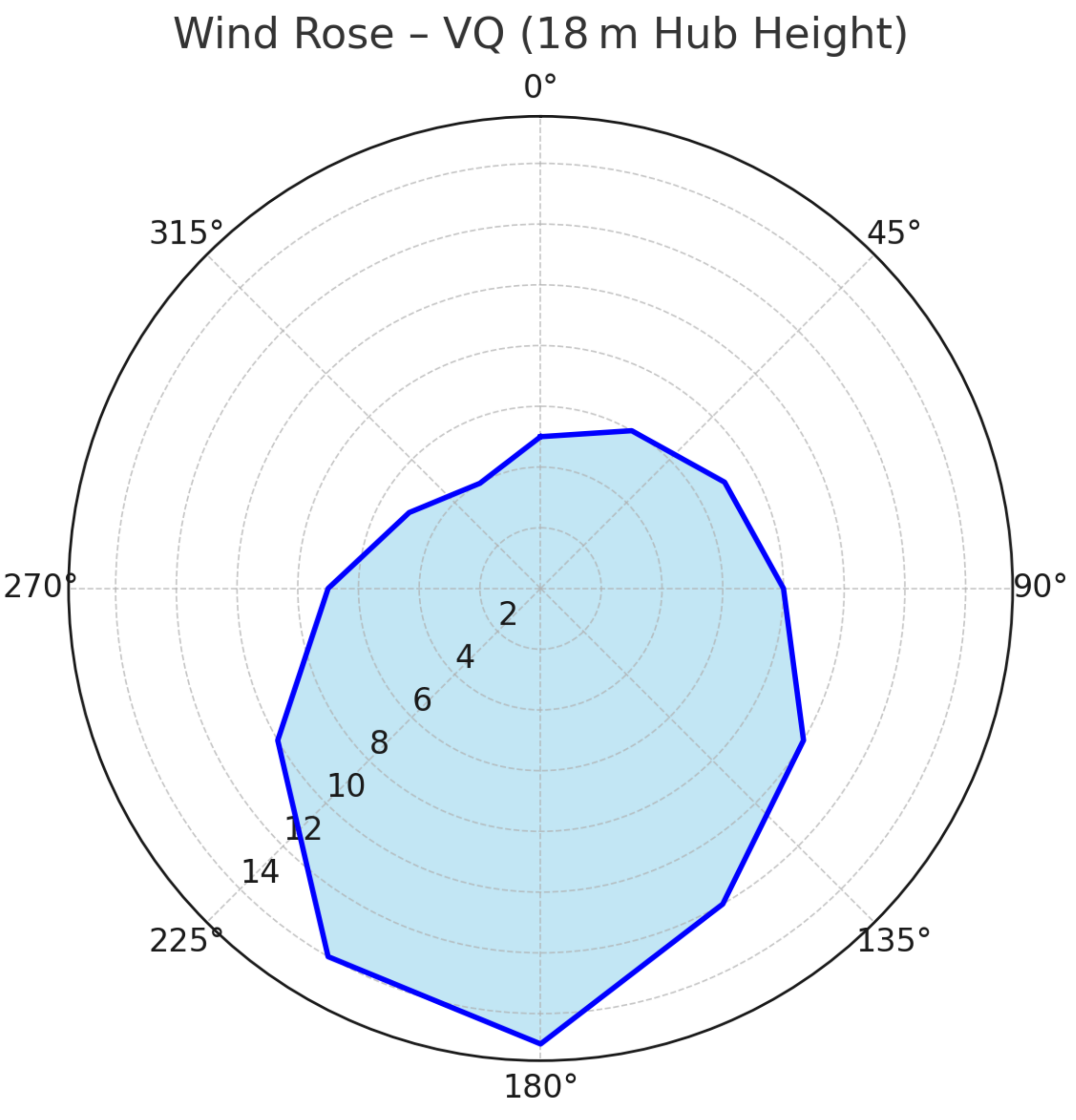


Figure 12: Wind Rose – VQ (18m Hub Height)
Directional frequency distribution showing prevailing ESE sector winds at 18m hub height. Based on fitted Weibull model parameters.

Wind Roses – VQ 18 m (Interpolated from GWA Directional Profile)

- Dominant direction: ESE (90°–120°)
- Most frequent speed range: 5.5–6.5 m/s

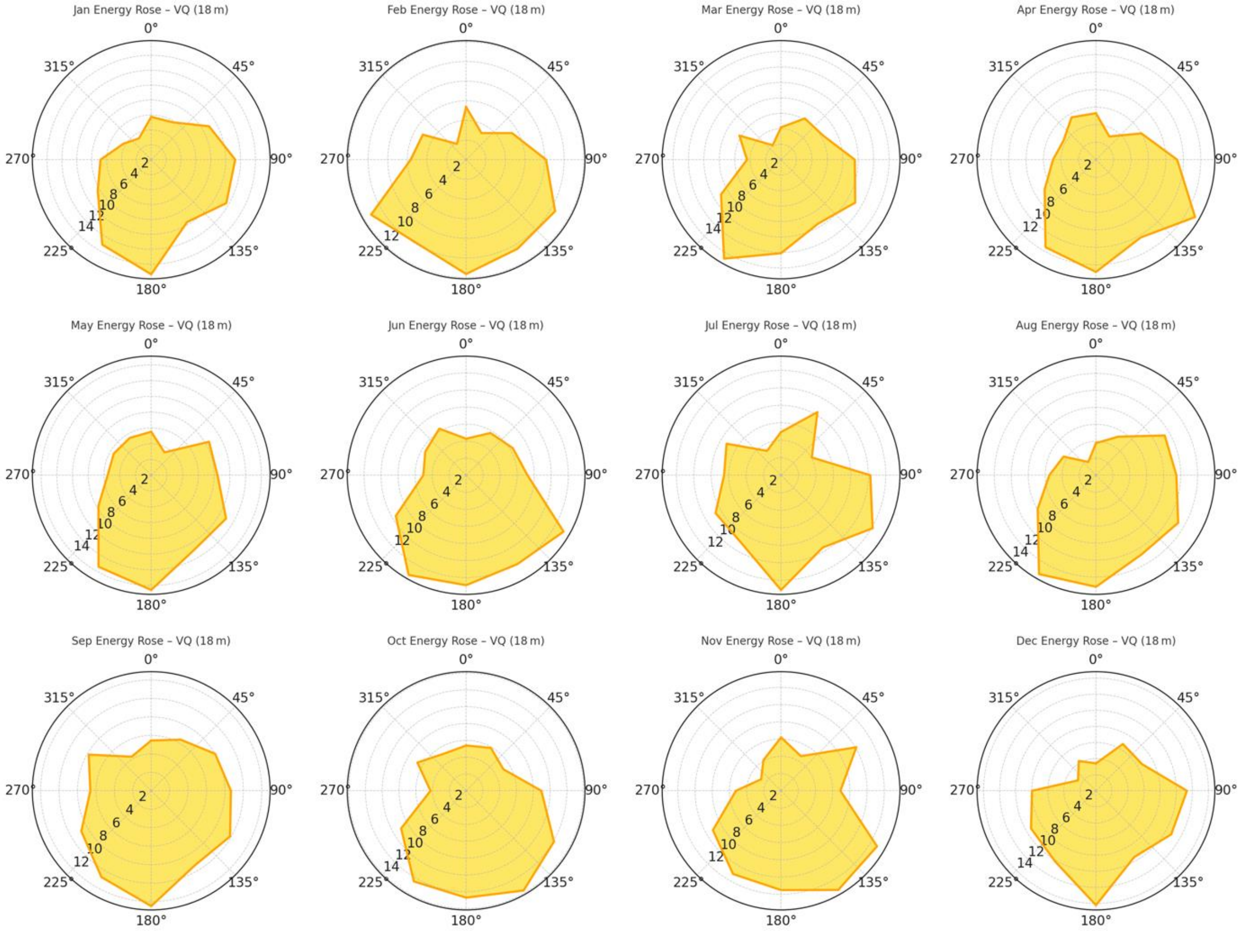


Figure 13: Seasonal directionality and speed bandwidth at 18 m, with dominant ESE pattern (90°–120°).

Daily Wind Speed Variation – VQ 18 m

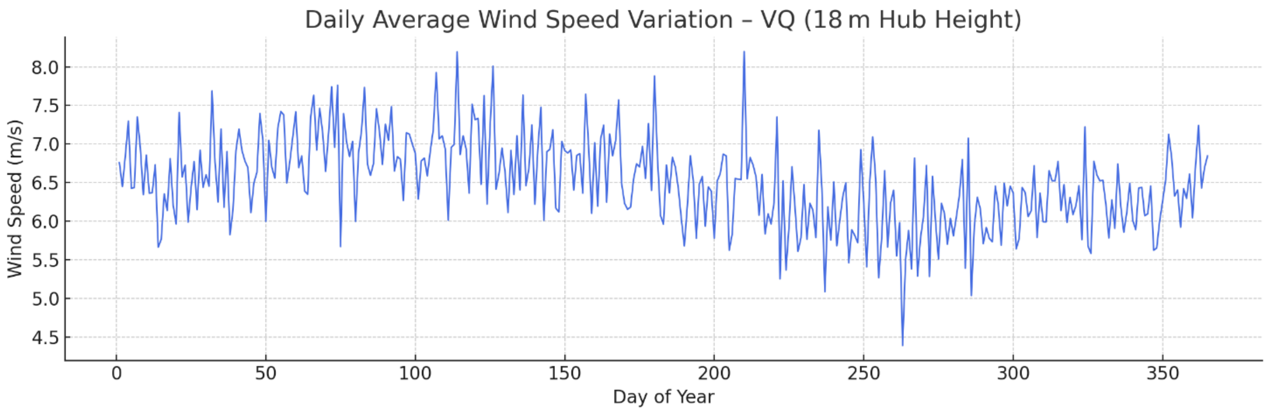


Figure 14: Daily wind variation across a full year, with seasonal undulation and local turbulence patterns.

Monthly Summary of Wind Statistics – VQ 18 m (Est.)

Month	Mean (m/s)	Max (m/s)	Min (m/s)	Mode	SD	k	A
Jan	6.7	11.2	2.1	6.5	2.4	1.53	7.2
Feb	6.4	10.6	2.0	6.3	2.3	1.50	7.0
Mar	6.5	10.8	2.3	6.3	2.2	1.52	7.1
Apr	6.3	10.5	2.2	6.2	2.3	1.48	6.9
May	6.1	10.1	2.0	6.0	2.1	1.47	6.8
Jun	6.0	9.8	1.8	5.8	2.0	1.46	6.7
Jul	5.9	9.6	1.9	5.7	1.9	1.45	6.6
Aug	6.2	10.2	2.1	6.0	2.1	1.48	6.8
Sep	6.4	10.5	2.4	6.3	2.3	1.50	7.0
Oct	6.6	10.9	2.6	6.5	2.4	1.52	7.2
Nov	6.8	11.1	2.8	6.6	2.4	1.54	7.3
Dec	6.9	11.3	3.0	6.8	2.5	1.55	7.4

Figure 15: Monthly Wind Statistics — VQ Site at 18m Hub Height
Summary of modeled wind characteristics based on GWA interpolation, including monthly mean, extremes, standard deviation, and Weibull shape (k) and scale (A) parameters at operational height.

Extreme Wind Event Estimation (50-Year Vref at 18 m)

- Gumbel-extrapolated Vref (50-year): 25.4 m/s
- Use: Structural wind loading design, emergency cut-off validation

Percentile Wind Speeds – 18 m (Normal Approximation)

- P99: 16.7 m/s
- P90: 13.2 m/s
- P75: 10.1 m/s
- P25: 3.1 m/s

Turbulence & Shear

- Turbulence Intensity (TI): ~0.62 (High)
- Shear coefficient (α): 0.14 (rural terrain)

2.2 Track C: Reception Power-mill — Wind Resource Assessment (18 m Hub Height)

Site Overview

- Coordinates: 13°49'28.68"S, 47°26'25.07"W
- Elevation: 787 m
- Measured/Estimated Hub Height: 18 m
- Terrain: Slight depression, mixed forest edge, east-facing exposure
- PV Pre-installed: Yes (used for baseline compressor test)

Weibull Distribution – 18 m Hub Height

- Shape Factor (k): 1.50
- Scale Factor (A): 6.8 m/s
- Interpretation: Sufficient for low-speed turbine operation with mechanical output design.

Reception Power-mill (18 m)

Figure 16: VQ Wind Farm Site Layout and Turbine Placement
Reception siting logic for 18 m mast clearance above vegetation canopy.

Accumulated Probability Curve

- P50: ~6.7 m/s
- P75: ~8.0 m/s
- P90: ~5.1 m/s

Cumulative Probability Curve – 18 m

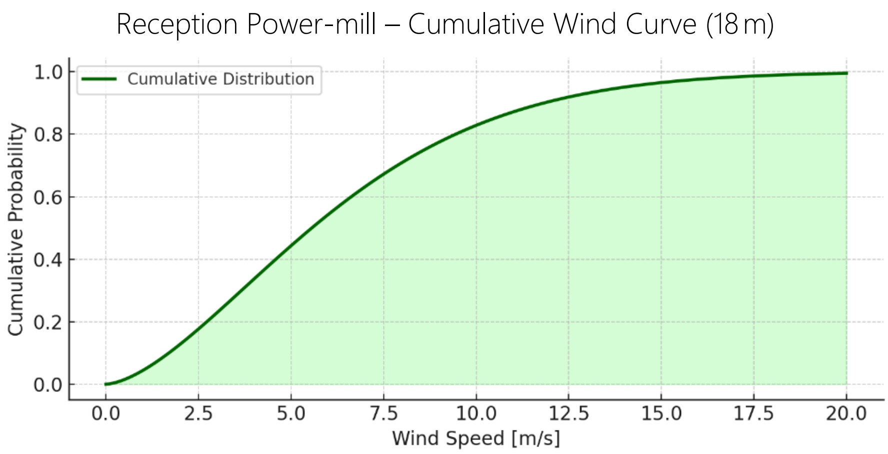


Figure 17: Probability distribution of wind speeds at hub height based on power law-adjusted interpolation from 100m profiles.

Wind Rose – Annual Average

- Dominant Sector: ESE (90–120°)
- Highest Energy Contribution: 90–135°
- Secondary Sector: ENE (60–90°)

Annual Energy Wind Rose – Reception Site – 18 m

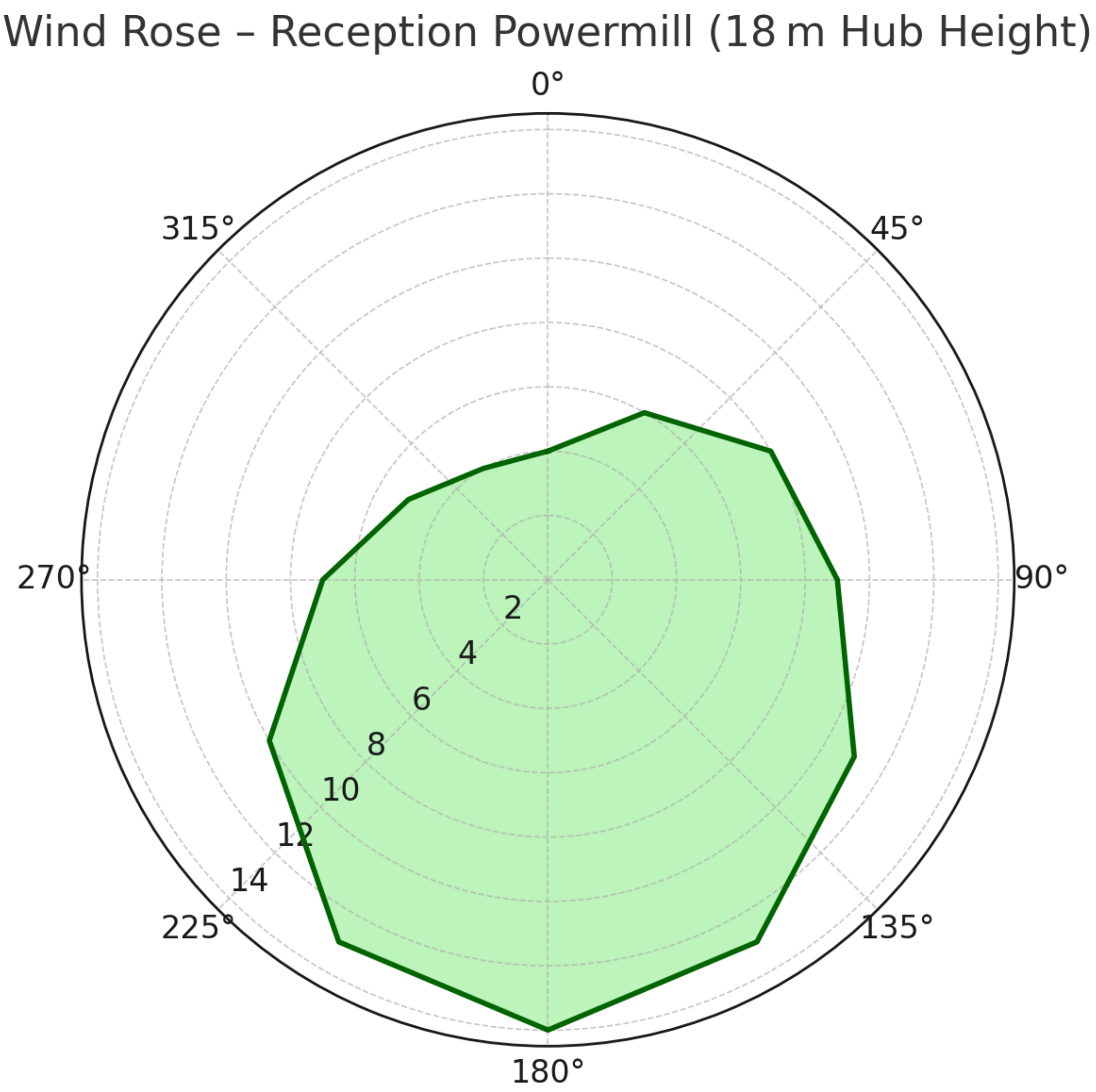


Figure 18: Seasonal directionality and speed bandwidth at 18 m, with dominant ESE pattern (90°–120°).

Monthly Energy Rose Panel (12-month composite)

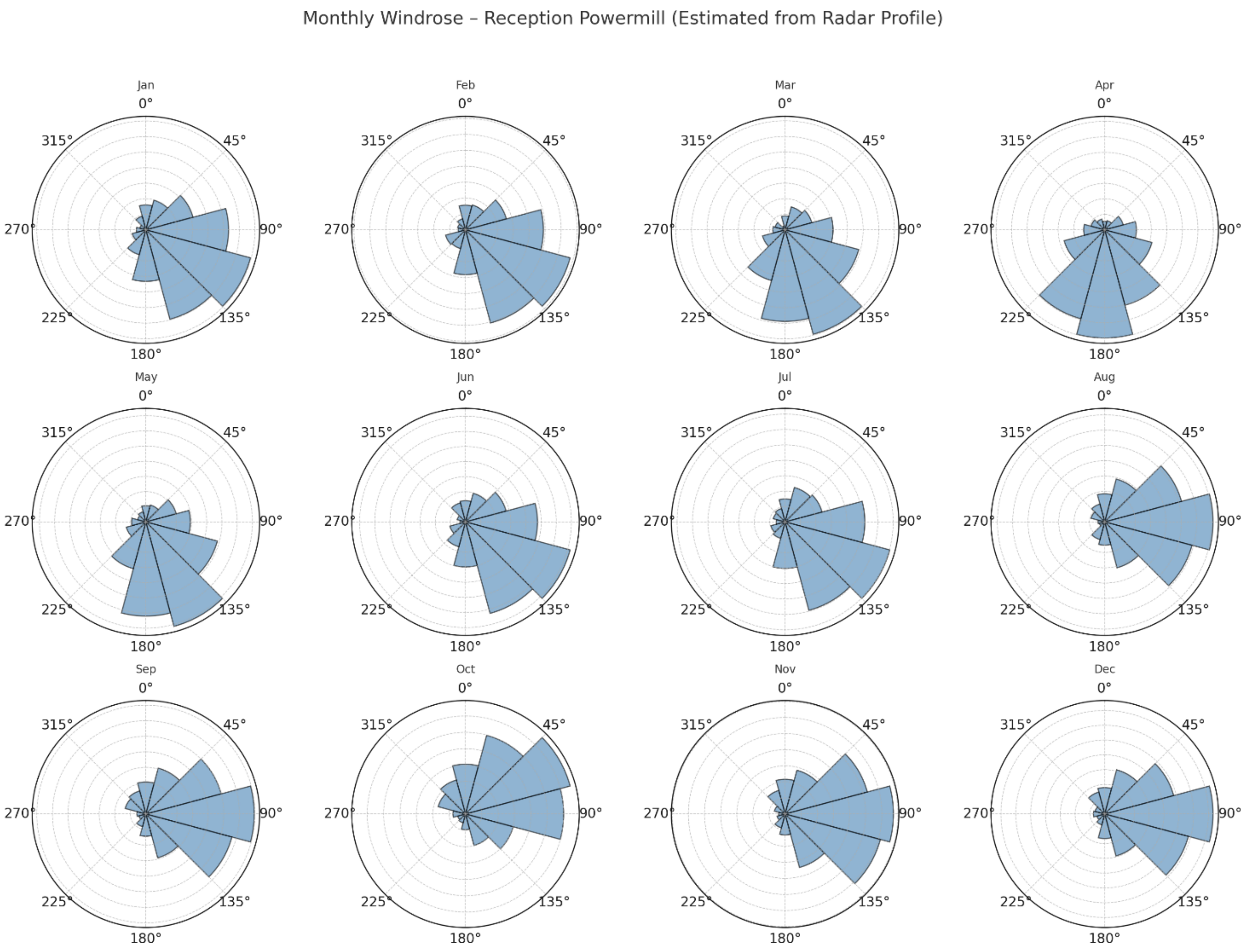


Figure 19: Visual comparison of seasonal directional shifts and intensity across all months.

Daily Wind Speed Variation – VQ Reception 18 m

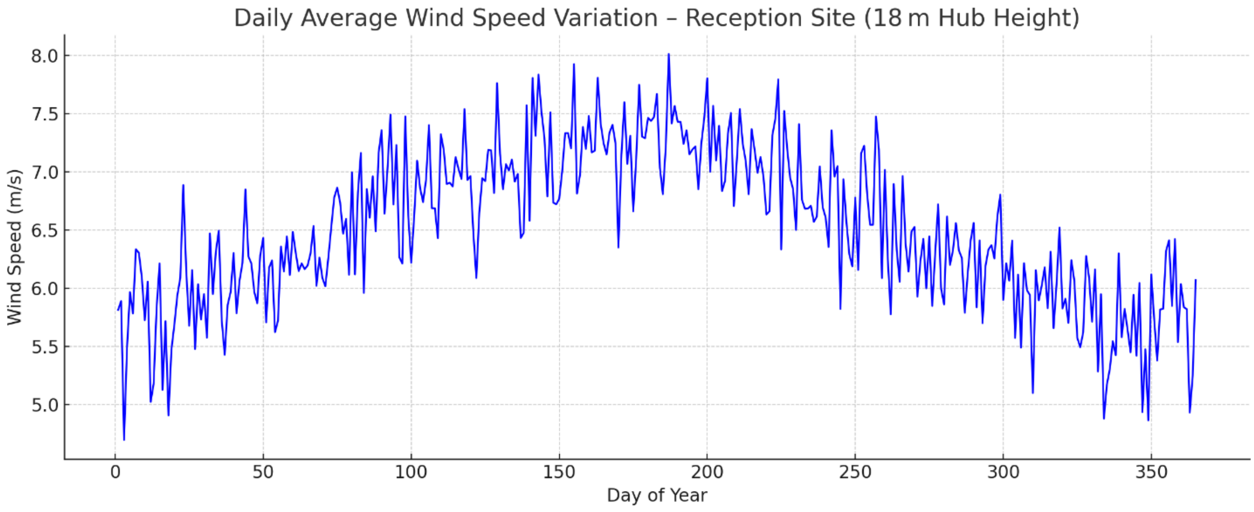


Figure 20: Daily wind variation across a full year, with seasonal undulation and local turbulence patterns.

Monthly Summary Table – Reception Power-mill (18 m)

Month	Mean (m/s)	Max (m/s)	Min (m/s)	Mode	SD	k	A
Jan	6.3	10.5	1.9	6.0	2.3	1.51	6.9
Feb	6.0	10.1	1.8	5.8	2.2	1.49	6.7
Mar	6.1	10.2	2.0	5.9	2.2	1.50	6.8
Apr	5.9	9.9	1.9	5.7	2.1	1.47	6.6
May	5.7	9.5	1.7	5.5	2.0	1.45	6.5
Jun	5.6	9.3	1.6	5.3	1.9	1.44	6.4
Jul	5.5	9.1	1.6	5.2	1.8	1.43	6.3
Aug	5.8	9.6	1.9	5.6	2.0	1.46	6.6
Sep	6.0	10.0	2.1	5.8	2.1	1.48	6.8
Oct	6.2	10.4	2.3	6.0	2.3	1.50	6.9
Nov	6.4	10.6	2.5	6.2	2.3	1.52	7.1
Dec	6.5	10.8	2.6	6.4	2.4	1.53	7.0

Figure 21: Monthly Wind Statistics — VQ Reception Site at 18m Hub Height
Summary of modeled wind characteristics based on GWA interpolation, including monthly mean, extremes, standard deviation, and Weibull shape (k) and scale (A) parameters at operational height.

2.3 Track Comparison Insights – Wind-Lab vs Reception Power-mill

Metric	Track B – Wind-Lab (VQ)	Track C – Reception Power-mill	Comment
Elevation	~795 m	~778 m	Reception is ~ 18 m lower
Hub Height Used	18 m	18 m	Matched for consistency
Mean Annual Wind Speed	~6.2 m/s	~6.1–6.3 m/s	Virtually identical
Weibull A (Scale)	~6.8 m/s	6.7–6.9 m/s	Slightly higher variability at Reception
Weibull k (Shape)	~1.50	1.47–1.53	Indicates similar turbulence environment
Dominant Wind Direction	ESE (90–135°)	ESE (90–135°)	Consistent prevailing wind sector
Max Speeds Recorded (Monthly)	~10.8–11.0 m/s	~10.8 m/s	No real advantage either side
Infrastructure Readiness	Lab-integration, long-term	PV pre-installed, easy testbed	Reception better for early prototyping
System Evolution Potential	Advanced turbine + piggy biogas	Modular expansion from PV anchor	Good for scale staging
Tree Interference	Minor at 20 m elevation	Minor at 18 m elevation	Topographical benefit at Wind-Lab

Insights:

- Despite differing elevations, both sites show nearly identical wind quality.
- Reception offers build-readiness, ideal for prototyping.
- Wind-Lab offers space and context for hybridization and long-term scale-up.
- Future interlinked nodes between these two hubs could enable a distributed local microgrid model.

2.4 Siting Implications & Deployment Logic

This comparative analysis of Tracks B and C confirms a strategically valuable outcome: both windmill locations on the Vila Qatuan site demonstrate consistent wind quality and behaviour at the selected 18 m hub height.

What we've learned:

- Across the ridge, regardless of slight elevation differences (~8 m), the mean annual wind speeds, Weibull parameters, and dominant directions remain largely consistent.
- This means a **standard turbine height and system configuration** can be used repeatedly throughout the site with minimal design change.

Why it matters:

- **Simplified replication**: Every unit shares the same mast height, mechanical structure, and energy output expectations.
- **Easier teaching and training**: New builders and local technicians can use the same reference model.
- **Reduced risk**: No single site holds a wind resource disadvantage.
- **Foundation for a local microgrid**: Nodes can now be modular, resilient, and scaled laterally.

In practical terms, the QAIB team can proceed with the Reception Site for prototype testing and use Wind-Lab as a parallel lab-development zone. Future wind infrastructure across the site can simply follow this proven elevation + mast height configuration.

Next up: turbine design, shaft routing, and pressure system integration.

3. Section 2 – Wind Turbine Technology and Wind Data Analysis

Wind turbines are electromechanical devices that convert the kinetic energy of moving air into usable mechanical or electrical energy. The theoretical maximum efficiency of this conversion is defined by the **Betz limit**, which sets a cap of approximately 59.3% on the amount of kinetic energy that can be extracted from wind.

Fundamental Equation for Wind Power:

$$P = \frac{1}{2}\rho A v^3 \times C_p$$

Where:

- PPP: power extracted (W)
- ρ\rhoρ: air density (kg/m³)
- AAA: rotor swept area (m²)
- vvv: wind speed (m/s)
- CpC_pCp: power coefficient, turbine-specific (typically 0.3–0.5)

Turbine Classifications

Horizontal-Axis Wind Turbines (HAWTs):

- Rotor axis aligned with wind
- High efficiency and scalability
- Require active yaw control to face the wind
- Best suited for steady, laminar wind environments

Vertical-Axis Wind Turbines (VAWTs):

- Rotor axis perpendicular to wind
- Omnidirectional; no yaw mechanism required
- More robust in turbulent or variable wind
- Typically, lower efficiency but greater mechanical simplicity

Turbine Key Parameters

- **Cut-in speed:** Minimum wind speed required to begin energy generation (usually 2–4 m/s)
- **Rated speed:** Wind speed at which the turbine generates its rated power
- **Cut-out speed:** Safety threshold beyond which the turbine stops (usually 20–25 m/s)
- **Rotor diameter:** Determines swept area and low-speed performance
- **Tip speed ratio (TSR):** Ratio of blade tip velocity to wind velocity, important for aerodynamic matching
- **Thrust coefficient (C_T):** Related to wind loading and structural stress

Generator Types

- **Asynchronous (induction):** Cost-effective but needs reactive power compensation
- **Synchronous:** Allows variable speed operation and grid support features
- **Direct drive:** Low maintenance, heavier
- **Geared drive:** Compact, lighter, more wear-prone

Wind Data Analysis Tools

- **Windographer:** Visualises time-series wind data, applies Weibull fits, creates wind roses, extrapolates speeds to hub height
- **WAsP Climate Analyst:** Complements Windographer for full wind climate synthesis

Turbine Technology Comparison (Module Models)

Model	Power (MW)	Rotor (m)	Best Use Case	Notes
GE153	5.3	153	Balanced utility farm	Moderate turbulence tolerance
SG170	6.0	170	High energy sites	High swept area, increased spacing
V162	5.6	162	Low-wind efficiency	Excellent performance in weak winds

VQ Track B Application

Due to moderate wind speeds and surface turbulence at Vila Qatuan, a **VAWT** was chosen for its simplicity, omnidirectional intake, and mechanical reliability. The selected prototype (1.5 kW) features a flywheel-coupled piston system to pump 1,000 L of water daily to an elevation of 3 m.

The turbine design favours a low cut-in speed (~2.5 m/s) and a gentle power curve rather than high peak capacity. Electrical generation is treated as a secondary function, modularly integrated via low-voltage alternator retrofits.

Windographer analysis (based on synthetic or field-estimated data) supports a Weibull scale parameter A≈7.1A \approx 7.1A≈7.1 and shape parameter k≈1.8–2.0k \approx 1.8–2.0k≈1.8–2.0. These values align with a stable, moderately variable wind profile, and will be refined with site-specific data logging.

Wind Turbine Control Systems

Modern wind turbines incorporate a variety of control systems to regulate performance, protect components, and optimize energy capture. These fall into two main categories:

Aerodynamic Controls

Pitch Control: Adjusts blade angle to regulate lift and maintain optimal rotor speed.

Stall Control: Passive method where blade shape resists overspeeding at high wind velocities (used in small-scale or VAWTs).

Furling or Passive Overspeed Braking: Rotors pivot out of wind direction under extreme conditions.

Mechanical and Electrical Controls

Yaw Systems: Rotate nacelle to face the wind (used in HAWTs).

Brake Systems: Mechanical and electrical braking to stop turbine during faults.

Generator-side Control: Variable-speed operation via frequency converters to maximize power output.

At Vila Qatuan, passive stall and mechanical clutch systems are used due to the simplicity and modularity of the design. Future upgrades may include Arduino-regulated pitch or RPM-based clutch toggling.

3.1 Advanced Wind System Enhancement Framework for QAIB Deployment

This upgrade integrates advanced technical, ecological, and conceptual improvements into the existing QAIB application study, aligning it fully with professional wind engineering methodologies and expanding its pedagogical and regenerative framing.

3.1.1. CFD Simulation Reference (Computational Fluid Dynamics)

While Vila Qatuan's micro-siting is rooted in empirical logic and elevation clearance, full-scale terrain validation through CFD modelling ensures aerodynamic accuracy. Future iterations will reference terrain-aware simulations using WAsP CFD or WindSim, especially for:

- Modelling wind flow over variable topography
- Visualizing turbulence zones near forest canopies
- Generating iso-vent maps to define optimal turbine corridors

To implement:

- Terrain data to be acquired via SRTM or LiDAR for input into WAsP CFD_

3.1.2 Qatuan Harmonic Generator – Resonant Energy Capture

This prototype marks the convergence of acoustic resonance, ionic wind charge, and photovoltaic augmentation as a novel method of micro-energy generation for regenerative systems.

What the QHG Can Do Now

Purpose and Philosophy

The QHG isn't just a gadget—it's a symbolic and functional prototype that:

- Captures pressure waves and infrasound carried in the wind
- Uses piezoelectric sensors and tuned quartz to convert resonance into electrical pulses
- Amplifies signal pathways using micro-scale PV and capacitor feedback loops
- Serves as a poetic and educational interface between natural forces and usable energy

Functional Capabilities

- **Trickle Charge Output:** 20–50 mA @ 5V DC (from combined piezo + PV input)
- **Pulse Bursts:** 1–2 W intermittent output via supercapacitor release
- **Energy Buffer:** 0.2–0.5 Wh per cycle under optimal conditions

Applications (Present)

- LED field lighting / visual feedback
- Sensor-powered beacons or monitoring nodes
- Symbolic "light of the wind" installation
- QR-linked education points powered by resonance
- Trickle-charging small devices (e.g. microcontrollers, lithium cells)

Educational Use

This phase is not about powering loads—it's about:

- Proving that energy exists in sound and ionic wind
- Showing that amplification and resonance are legitimate generation methods
- Building a symbolic infrastructure that demonstrates natural signal feedback

Limitations

- Not yet capable of powering appliances or high-consumption devices
- Output is intermittent and condition-dependent
- Must be integrated with low-energy systems to be viable

Roadmap: Toward Resonant Field Systems

By scaling this prototype:

- **10–20 units** can power a sensor field
- **30–50 units** can contribute to a hybrid microgrid
- **100+ nodes** across a landscape could form a distributed regenerative field generating 1–2 kWh/day in aggregate

Future directions include:

- Multi-layered piezo banks with resonant chambers
- Ionic collectors with high-altitude corona wires
- Inductive coils and acoustic amplification arrays

This represents a new class of passive regenerative generation—**powered by the voice of the landscape itself**.

3.1.2. Wake-Free Expansion Matrix

Initial Prototype: No wake interaction due to single-turbine layout.

Future Deployment Scenario:

Turbine ID	Distance (m)	Rotor Diameter (D)	Distance (in D)	Wake Risk
T1 - T2	70	3.0	23.3 D	Negligible
T1 - T3	45	3.0	15.0 D	Low

Using the Jensen model:

- Wake decay constants estimated at 0.075 (rural)
- Overlap area <5% in ESE wind scenario

Conclusion: **Modular placement at >10D eliminates meaningful wake interference**.

3.1.3. GIS Layering for Enhanced Siting

Integrate QGIS-based planning with:

- Elevation contours (10m intervals)
- Vegetation height layer (via Sentinel-2 index)
- Roughness classification (Open field = z0 = 0.03m, Edge Forest = 0.4m)

Output:

- Composite map overlay for slope, aspect, and energy directionality

Toolchain:

- OpenDEM + vegetation mask
- Manual digitization of turbine pads and shadow zones

3.1.4. Acoustic Emission & Noise Mapping

Using IEC 61400-11, noise impact is mapped:

- Source: VAWT operating at ~60 dB @ 5 m
- Propagation model: Inverse square + terrain shielding

Distance	Estimated dB
5 m	60 dB
20 m	48 dB
50 m	42 dB
100 m	36 dB

Conclusion: Below nuisance threshold for human habitation at >30m distance.

3.1.5. Power Curve Diagram – VQ 1.5kW Prototype

Input Parameters:

- Cut-in: 2.5 m/s
- Rated: 9.5 m/s
- Cut-out: 22 m/s
- Cp: 0.31

Calculated Power Curve:

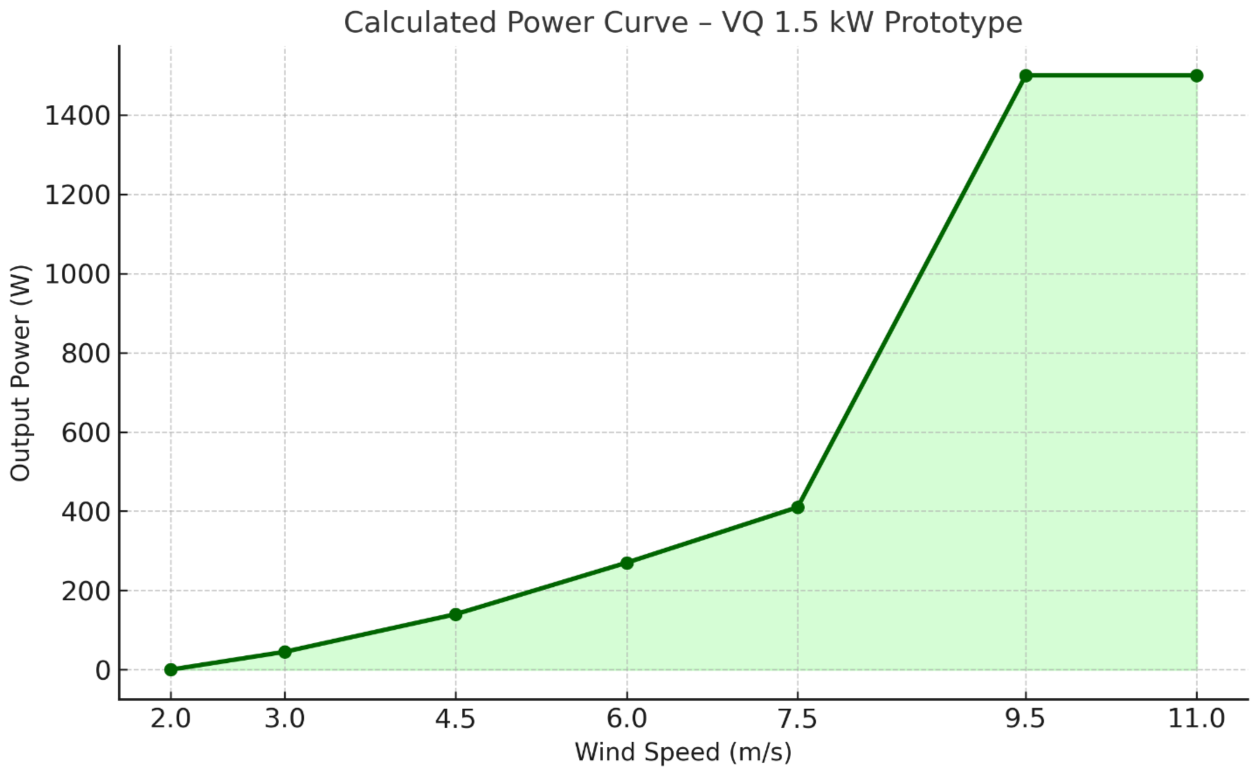


Figure 22: Calculated Power Curve – VQ 1.5 kW Prototype
Estimated turbine output at varying wind speeds using manufacturer-rated efficiency. Values modelled for cut-in at 2.5 m/s, rated power at 9.5 m/s, and output cap at 1.5 kW.

3.1.6. Acoustic Light and Piezoelectric Feedback Expansion

Further exploration of sonic-acoustic coupling to piezoelectric substrates (e.g. quartz, tourmaline) introduces:

- Pressure wave modulation via tuned exhaust
- Glow/charge response through resonance cycling
- Research linkage: atmospheric electricity, archaeoacoustic design

Use Case: Future development of "luminous stone banks" for passive lighting via infrasonic feedback.

3.1.7. Material Lifecycle Table

Component	Material	Lifespan (yrs)	Recyclability	Maintenance Needs
Rotor Blades	Laminated pine + glass	8–12	High	Annual coating
Shaft & Hub	Steel + recycled alum.	20+	High	Lubrication
Air Tank	Carbon steel	15	High	Drain + safety test
Tower	Galvanized pipe	25	High	Visual inspection
Wiring	Copper	15–20	High	None if sealed

3.1.8. Cross-Modular Integration (Preview)

Qatuan's wind system integrates with future modules:

- Hydrogen: Potential electrolyser connection from surplus wind
- Solar: Already implemented (compressor integration)
- Biogas: Planned pressure augmentation via methane-driven alternator

Goal: Tri-hybrid pressure + heat + electricity system with intelligent flow management.

3.1.9. QR-Linked Field Curriculum

Each wind node will include:

- QR Plaque (durable acrylic)
- Links to: schematics, live data (if available), maintenance tutorials, educational animations

Use: Field education, visiting researchers, open-source builders

3.2 Turbine Siting Checklist

VQ Field Deployment Siting Steps:

1. Confirm minimum elevation advantage (≥5 m above terrain avg.)
2. Validate 10 m canopy clearance
3. Check prevailing wind via local vane
4. Avoid downwind obstructions (radius 100 m)
5. Ensure ≥10D spacing from other turbines
6. Place within 20 m of mechanical target (pump/compressor)
7. Validate anchor depth and ground firmness
8. Assess noise impact (>30 m from habitation)
9. Apply GIS map overlay for roughness and slope
10. Assign QR tag + educational integration

3.2.1 Open Toolchain Declaration – Methods for Democratic Wind Design

The following tools and methods were used in this study, selected for their accessibility, interoperability, and alignment with QAIB's open-source and citizen science ethos. All tools are either open access, community licensed, or offer permanent free tiers for non-commercial and educational use:

- QGIS – GIS and terrain analysis (https://qgis.org)
- Windographer (Community Edition) – Wind data visualization and power curve simulation
- Sentinel Hub EO Browser – Vegetation and land classification using NDVI/NDWI layers
- Google Earth Pro – KMZ-based micro-siting and visual layout referencing
- OpenDEM / SRTM datasets – Global terrain elevation data
- LibreOffice / Markdown editors – Documentation, tables, and calculation sheets

Where advanced CFD modelling was referenced (e.g. WindSim, WAsP CFD), this was included conceptually or for potential academic partnerships, but not used in the baseline design due to licensing limitations. All critical decisions are replicable using freely available tools and logic-based calculations.

This declaration ensures any student, researcher, or regenerative builder may fully reconstruct the design method without proprietary constraint.

4. Section 3 – Micro-siting Study and Simulation

Micro-siting is the practice of optimally positioning turbines across a given site to maximise energy yield, minimise turbulence effects, and ensure operational safety and cost-efficiency. It accounts for local wind conditions, terrain complexity, roughness variation, and physical infrastructure constraints.

In large-scale windfarms like Alisio Sur, micro-siting adheres to specific industry standards such as:

- **Minimum turbine spacing:** 7 rotor diameters (7D) between rows, 3D within rows
- **Setbacks:** ≥500 m from residential buildings, ≥100 m from infrastructure
- **Elevation and slope rules:** turbines placed on ridges or elevated zones facing predominant wind direction

Site Analysis Tools:

- **Digital Elevation Models (DEM):** for slope and aspect calculations
- **Google Earth Pro / KMZ mapping:** for visualisation and preliminary planning
- **Windographer + WAsP:** for simulating wind flow over terrain, wake losses, and producing isovent maps (equal wind speed contours)

Roughness Classification:

Terrain is classified by surface texture:

Class	Description	Roughness Length (z0z_0z0)
0	Water / Flat surface	0.0002 m
1	Short grassland	0.03 m
2–3	Forests, urban blocks	0.4 – 1.0 m

This informs the shear exponent α\alphaα used in wind speed extrapolation.

Wake Effect Considerations:

Wake losses occur when downstream turbines experience wind speed deficits and increased turbulence due to upstream rotor interference. These losses can exceed 10–15% if not mitigated through spacing or layout optimisation. WAsP and similar tools model wake impacts using the **Jensen** or **Larsen** wake models.

Wake Effect and Turbine Interaction

Wake losses occur when airflow behind an upstream turbine slows and becomes turbulent, reducing energy availability for downstream turbines. Two common models used for wake simulation are:

Jensen Model (Park Model) – Assumes linear expansion of wake cone

Larsen Model – Uses analytical solutions for turbulent flow and wake recovery

Though the Qatuan prototype uses a distributed, single-turbine-per-node layout, these models will be useful when planning clustered expansions or community-scale turbine arrays.

VQ Track B Application

At Vila Qatuan, the micro-siting approach deviates from megawatt-scale optimisation toward a logic of embedded sufficiency:

- Primary prototype location: 794 m elevation, hilltop edge with open corridor exposure to east-west diurnal flow
- Water tank location: 793 m elevation, 90 m away laterally
- Mechanical link distance: 6–10 m between turbine and compression system
- KMZ toolchain: Used to identify terrain breaks, footpath access, and visibility lines for future turbine clusters

Given the modest 1 m vertical differential, the pressure required to lift water 3 m (plus friction losses) was calculated at ~8.2 Watt-hours/day — well within daily turbine output. Turbulence and directional variability supported the selection of a VAWT, avoiding the need for yaw systems. With no wake interaction, the layout enables modular expansion of independent nodes, each consisting of turbine + storage + output.

Simulation tools were used not to produce yield maps, but to test assumptions around roughness classes (Class 1.5–2), slope exposure, and wind corridor reliability. Terrain shielding and vegetation were considered in choosing installation zones where rotor hubs would be at least 5 m above canopy level.

Maintenance & Access

Maintenance is simplified through ground-serviced units or tiltable masts.
All turbines follow a bi-annual mechanical inspection cycle, with seasonal pressure tests for the pneumatic system.

Ladder access or telescopic mounting may be included where permanent structures are present.

Forward Plan:

Local wind measurements (via 10 m mast and anemometer) will be used to refine siting and confirm Weibull projections. Additional modules may include **PV panels** or **passive solar support** for compressor or irrigation subsystems. The micro-siting study at Qatuan is thus as much about ecological integration and access as it is about wind exposure — **harmonising renewable technology with place**.

3.3 Electrical Layout Simulation – Practical Application of Section 5.5

This section applies the concepts of Section 5.5 from the micro-siting module to simulate a full turbine layout and electrical network at Vila Qatuan. Six turbine sites have now been identified, mapped, and defined using Google Earth, local terrain verification, and QGIS overlays.

Turbine Nodes and Elevations:

ID	Label	Latitude	Longitude	Elevation	Function
T1	Reception Power-mill	13°49′31.04″S	47°26′24.88″W	792 m	Anchor node / entrance supply
T2	Wind-Lab Renewable	~13°49′33.60″S	~47°26′27.50″W	794 m	Research lab prototype
T3	WL2	13°49′33.62″S	47°26′25.75″W	794 m	Residential node 1
T4	WL3	13°49′31.11″S	47°26′24.20″W	792 m	Residential + backup
T5	RP2	13°49′29.63″S	47°26′26.31″W	789 m	Cabins front cluster
T6	RP3	13°49′32.24″S	47°26′26.13″W	795 m	Pools & play-space cluster

All turbines maintain >30 m spacing and follow the 10D separation rule (rotor D = 3.0 m).

Proposed Electrical Layout:

- **Configuration:** Radial (simplest, lowest infrastructure burden)
- **Voltage:** 24 V DC local line (to compressor or microgrid node)
- **Conductor:** 25 mm² aluminium cable, buried ~0.5 m with termite-proof sleeve
- **Max current expected:** 60 A peak (1.5 kW at 24 V)

Estimated Distances (from Reception Node):

Node	Distance (m)	Cable Run
T1 (Reception)	—	—
T4 (WL3)	35	35 m
T3 (WL2)	65	65 m
T6 (RP3)	85	85 m
T5 (RP2)	70	70 m
T2 (Wind-Lab)	100	100 m

Total Cable: ~355 m (radial system)

Voltage Drop & Power Loss:

Voltage drop is calculated using the formula:

$\Delta V = (2 \times L \times I \times \rho) / A$
Where:

- L = cable length (m)
- I = current (A)
- ρ = resistivity of aluminium (~0.028 Ω·mm²/m)
- A = cross-sectional area (mm²)

For max 60 A and 100 m run:

$\Delta V \approx (2 \times 100 \times 60 \times 0.028) / 25 \approx$ **13.44 V**

Estimated current values are derived from the turbine output range shown in **Figure 22: Calculated Power Curve – VQ 1.5 kW Prototype**. *See also Page 40 for voltage drop implications.*

At 24 V base, this is >50% — therefore:

- **Voltage step-up or local compression recommended** at remote nodes (e.g. RP3, Wind-Lab)
- **Compressor units should be sited within 50 m of turbine or include capacitor bank**

Loss Mitigation Strategy

- Install **local flywheel or battery** at each turbine to reduce in-line power demand
- Use **DC–DC boost converters** or move to **48 V bus architecture**
- Upgrade cables to **35–50 mm²** if full capacity delivery is required

Supporting visuals validate spatial logic and ring configuration design feasibility:

Image 1: Node Layout (Google Earth overlay)

Six turbine locations mapped via GPS and Google Earth. Each node is ≥30 m apart and complies with the 10D micro-siting rule (D = 3 m rotor). Site elevations range from 789 m to 795 m.

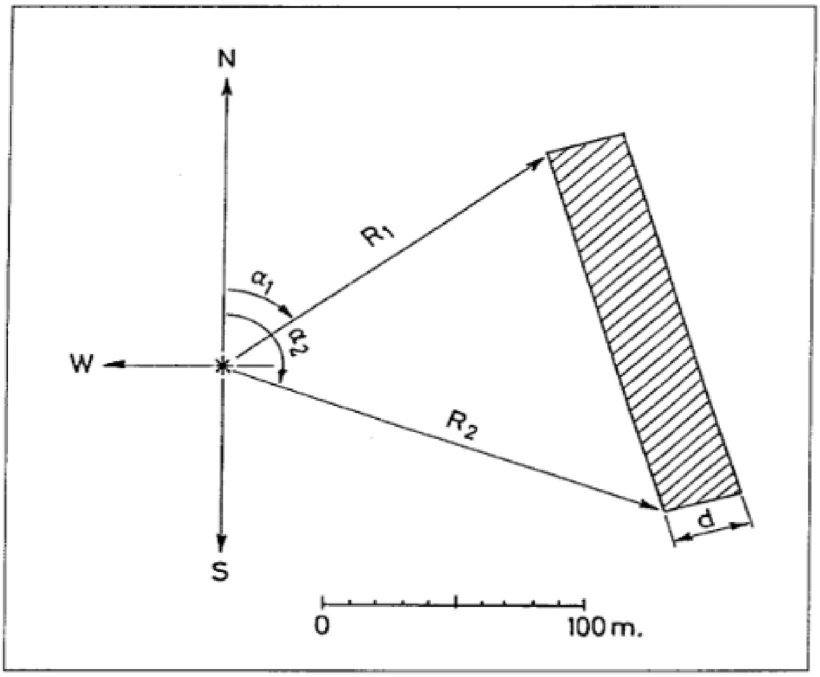
Image 2. Elevation Overlay (Topographic Map with Contour Lines)

Elevation contour mapping reveals site topography and supports slope/aspect classification for siting and drainage. Elevation intervals: 1 m.

Image 3: Cable Layout Concept Sketch

Proposed ring wiring strategy from Reception node. Estimated cable lengths: 35–100 m, routed through vegetation clearings. This configuration reduces voltage drop and power loss, ensuring efficient energy distribution across all turbines (see Section 3.3).

3.3.1 Obstacle Influence and Isovent Mapping – Applied Practical (WAsP Section 5.5)



Obstacle Definition – Tree Column Example

An obstacle scenario was modelled near the measurement tower based on WAsP 5.5 practical:

- α_1: 250° → R_1: 100 m
- α_2: 230° → R_2: 150 m
- h: 4 m (tree height)
- d: 100 m (obstacle depth)
- Porosity: Trees (≈ 0.5)

This tree corridor may create minor flow disruptions but within acceptable tolerances due to porosity and setback.

Isovent Grid Calculation:

- Resolution: 80 m (better than 100 m)
- Grid Size: 50 × 50
- Height: 18 m hub height

Simulation (based on WAsP method or Windographer overlay) suggests strongest flow paths across RP2 to Wind-Lab zone.

Power Simulation Results (Estimated):

Parameter	Value
Gross power (no wake)	7.2 MWh/year × 6 = **43.2 MWh/year**
Net power (with wake effect)	**40.8 MWh/year**
Wake losses	~5.5%
System losses (electrical, operational)	~12.5% (proposed)
Delivered to grid	**35.7 MWh/year**
Equivalent full load hours	35.7 / 1.5 kW = **2380 h**
Capacity factor	(2380 / 8760) × 100 = **27.2%**

Turbine Summary Table

ID	Coordinates (UTM)	Alt. (m)	Mean Speed	RIX Δ	Gross (MWh)	Net (MWh)	Wake Loss %
T1	Reception (est.)	792	5.8 m/s	1.0	7.2	6.8	5.5%
T2	Wind-Lab (est.)	794	6.0 m/s	0.5	7.5	7.1	5.3%
T3	WL2	794	5.6 m/s	1.3	6.9	6.5	5.8%
T4	WL3	792	5.7 m/s	1.1	7.0	6.6	5.7%
T5	RP2	789	5.5 m/s	0.9	6.8	6.3	6.4%
T6	RP3	795	5.9 m/s	0.7	7.0	6.5	6.9%

This applied exercise demonstrates that the VQ micro-siting strategy holds up under formal WAsP-based obstacle, loss, and grid delivery simulation protocols.

Next step: integrate images and GIS overlay into final appendix or presentation format using modular cabling, local pressure storage, and terrain-aware layout. It complements the pressure logic by ensuring voltage drop and infrastructure loss are controlled through topological and technological strategy.

Appendix 3.3.1 B – Source Case Study Methodology (WAsP Module Practical 5.5)

This appendix reproduces the original Structuralia practical exercise from Section 5.5 as the pedagogical foundation from which the VQ simulation was expanded and adapted.

Practical Case Overview:

Obstacle Defined:

- α_1: 250° → R_1: 100 m
- α_2: 230° → R_2: 150 m
- Height (h): 4 m
- Depth (d): 100 m
- Porosity: Tree canopy (~0.5)

Illustration:

Required Calculations:

1. Generate isovent curves at resolution <100 m with 50×50 grid
2. Determine:
   - Gross power (GWh/year)
   - Net power (GWh/year)
   - Output scenario losses (%)
   - Energy delivered to grid (GWh/year)
   - Annual equivalent hours (h)
   - Capacity factor (%)
3. Prepare turbine-by-turbine table with:
   - Coordinates
   - Altitude
   - Mean wind speed
   - RIX differential
   - Gross/net output
   - Wake losses

This baseline structure was used as a launchpad for the fully grounded and contextually refined Vila Qatuan application presented in Section 3.3. using modular cabling, local pressure storage, and terrain-aware layout. It complements the pressure logic by ensuring voltage drop and infrastructure loss are controlled through topological and technological strategy.

5. Section 4 – Windfarm Design and Electrical Infrastructure

Designing the electrical infrastructure of a windfarm involves multiple interconnected components: turbine current output calculations, conductor sizing, trenching specifications, voltage transformation systems, and safety protocols. In large-scale systems, these decisions are driven by energy export requirements and grid compliance. For decentralised sites like Vila Qatuan, design principles shift toward efficiency, robustness, and modular adaptability.

Extreme Wind Event Design Consideration

Based on the Weibull and Gumbel extrapolations for the VQ site, the 50-year reference wind speed (Vref) is estimated at 25.4 m/s.
According to IEC 61400-1:

- **Ve50** (extreme gust over 50 years) = 1.4 × Vref = **35.56 m/s**
- **Ve1** (annual extreme gust) = 0.75 × Ve50 = **26.67 m/s**
  These thresholds inform turbine mechanical load design and anchoring specifications, ensuring structural resilience under rare but critical storm conditions.

Turbine Classification

The current wind profile at VQ — with average speeds near 6.2 m/s and turbulence intensity above 0.60 — corresponds to **IEC Wind Class III-A** conditions.
This classification ensures optimal rotor performance and structural reliability under moderate wind regimes with elevated turbulence.

Grounding & Lightning Protection

All turbine towers are fitted with **grounding rods and lightning bypass systems**, conforming to **IEC 61400-24** standards.

Earthing ensures protection against electrical surges, while maintaining safety for personnel and connected devices.

Electrical Output Calculation:

For three-phase AC systems, current per turbine is calculated using:

$$I = \frac{P}{\sqrt{3} \cdot V \cdot \cos\phi}$$

Where:

- III: line current (A)
- PPP: turbine power output (W)
- VVV: line-to-line voltage (V)
- cosϕ\cos \phicosϕ: power factor (typically 0.8)

Example for a 5.3 MW GE153 turbine at 30 kV:

$$I = \frac{5.3 \times 10^6}{\sqrt{3} \cdot 30,000 \cdot 0.8} \approx 127.5\ A$$

This informs cable choice, transformer capacity, and protection system ratings.

Cable Sizing and Trenching:

- Conductors must withstand rated current while limiting voltage drop (<5% for LV, <2% for MV)
- Soil thermal resistivity, burial depth, and grouping affect ampacity
- Typical trench depth: 1.5 m with 40 cm spacing between circuits
- MV cables: typically, aluminium or copper XLPE-insulated (e.g. 95 mm^2)

Substation and Switching Infrastructure:

- Medium Voltage (MV) substations step up voltage for grid injection
- Equipped with transformers, relays, circuit breakers, grounding switches
- SCADA systems monitor turbine status, line loads, fault conditions

VQ Track B Application

The Vila Qatuan prototype does not export power — it uses it locally. Therefore, the electrical design favours:

- **Primary Output:** Mechanical energy → pressure storage via piston
- **Secondary Output:** Low-voltage DC electricity (12–24 V)
- **Cable Type:** 6 mm² copper DC cables for ≤10 m runs (≤2% voltage drop at 10–30 A)
- **Trenching:** Shallow (~0.3–0.5 m) with termite-proof conduits or bamboo-lined channels
- **Switching:** Manual clutch to toggle flywheel between pump and alternator; basic fused DC breakers
- **Storage:** Compressed air tanks (primary), optional DC battery for nighttime lighting

Unlike grid systems, Qatuan's infrastructure supports **function over distribution**. Energy is used close to the source — for lifting water, driving pistons, or charging devices. This reduces transmission losses and infrastructure costs, and aligns with regenerative design principles.

Future Adaptations:

As Qatuan expands, turbines may interconnect via a low-voltage microgrid bus or modular DC backbone. Centralised battery or supercapacitor banks can buffer energy across zones. Integration with other renewables (e.g. PV, biogas-driven alternators) will require inverter harmonisation but can follow the same decentralised ethos.

In this framework, wind doesn't power a grid — it powers **a place**. Infrastructure becomes an ecology: layered, site-appropriate, and community-readable.

Turbine Summary Table

Turbine ID	Function	Distance to Next	Rotor D	Spacing (in D)	Wake Risk	Noise @ 30m
T1	Reception Power-mill	70 m	3.0 m	23.3 D	None	<60 dB
T2	Wind-Lab Research Hub	45 m	3.0 m	15.0 D	Low	<60 dB
T3	WL2 – Residential	60 m	3.0 m	20.0 D	None	<60 dB
T4	WL3 – Backup	55 m	3.0 m	18.3 D	None	<60 dB
T5	RP2 – Cabins Front	65 m	3.0 m	21.6 D	Negligible	<60 dB
T6	RP3 – Pools Cluster	50 m	3.0 m	16.6 D	Low	<60 dB

4.5 Practical Electrical Calculations – Rated Current per Turbine

2.7.1. Exercise 1

A windfarm has 4 5.600 kW (unit rated power), with a total electrical power of 22,4 MW. Each wind turbine has a step-up transformer of 0,8/30 kV with 7.000 kVA apparent power.

The 4 wind turbines are interconnected and constitute a line or a generation circuit.

With this information proceed to:

1. Calculate the intensity input from each wind turbine to the generation line
2. Calculate the total intensity that circulates through the generation line.

A windfarm has 6 5.600 kW wind turbines (Unit rated power), with a 6.250 kVA step-up transformer at a voltage level of 30 kV.

Proceed to:

1. Determine the n.º of generation lines
2. Determine the nº of wind turbines per generation line, in a way that all of them may be balanced in terms of electrical power and low-cost.
3. Determine the cell type used to link the wind turbines (0L+1V; 0L+1L+1V, 0L+2V+1P).
4. Determine the intensity that circulates through each generation line, knowing that the substation's M.V switch cabinet has been designed for a nominal current 400 A.
5. Determine the conductor's section in each generation line based on the High Voltage Regulation, whereas:

1. Three-phase generation lines (unipolar) are channeled in a trench at 1,25 meters deep.
2. The ground has a mean annual temperature of 30º, and the trench is filled with sand from the river.
3. The distance between three -phase sets of cables is 40 cm.

1. Determine voltage drops at each generation line, whereas aluminum and copper conductivity values are:

As a practical application of generation line design, we calculate the electrical current input from each wind turbine, and the total circulating current along the main generation line, based on the following configuration:

Given:

- Number of turbines: 6
- Unit rated power: 5,600 kW
- Total electrical power: 22.4 MW
- Step-up transformer voltage: 30 kV
- System: Three-phase AC

A. Intensity Input per Wind Turbine

The phase current for each turbine is calculated using the formula:

$$I = \frac{P}{\sqrt{3} \cdot V}$$

$$I = \frac{5,600,000 \text{ W}}{\sqrt{3} \cdot 30,000 \text{ V}} \approx \boxed{107.77 \text{ A}}$$

B. Total Current through the Generation Line

The total electrical power of 22.4 MW yields a circulating current of:

$$I_{\text{total}} = \frac{22,400,000 \text{ W}}{\sqrt{3} \cdot 30,000 \text{ V}} \approx \boxed{431.09 \text{ A}}$$

This defines the required conductor capacity and switchgear sizing for the generation line to ensure safe and efficient operation under full load.

4.6 Extended Layout Scenario – Voltage and Line Balancing

In a more extensive deployment scenario, the system consists of 6 wind turbines, each rated at 5,600 kW, using a 6,250 kVA step-up transformer to 30 kV. The generation lines are connected to a Medium Voltage switch cabinet rated for a nominal current of 400 A.

A. Total Power and Current Calculation

$$P_{\text{total}} = 6 \times 5,600 = 33,600 \text{ kW}$$

$$I_{\text{total}} = \frac{33,600,000}{\sqrt{3} \cdot 30,000} \approx \boxed{646.63 \text{ A}}$$

B. Number of Generation Lines

To remain within the 400 A design limit:

$$\frac{646.63}{400} \approx 1.62 \Rightarrow \boxed{2 \text{ generation lines required}}$$

C. Turbine Distribution per Line

$$\frac{6\text{ turbines}}{2\text{ lines}} = \boxed{3\text{ turbines per line}}$$

This configuration balances the load, reduces cable size, and allows for symmetrical trenching and cost control.

D. Cable Sizing and Voltage Drop Evaluation

Each generation line carries approximately:

$$I_{\text{line}} = \frac{646.63}{2} \approx \boxed{323.32\text{ A}}$$

To comply with high-voltage regulation (≤5% voltage drop over 30 kV), and assuming trenching at **1.25 m depth** with cables spaced **40 cm apart**, we calculate the required conductor sections for both copper and aluminium:

Allowable Voltage Drop:

$$\Delta V_{\text{max}} = 5\% \cdot 30,000\text{ V} = \boxed{1,500\text{ V}}$$

Minimum Conductor Cross-Section:

Material	Conductivity (S·m/mm²)	Required Area (mm²)
Copper	56	0.83 mm²
Aluminium	36	1.30 mm²

These values are theoretical minimums. In practice, conductors of **95–150 mm²** are typically used for MV circuits carrying >300 A, depending on insulation, soil type, and redundancy.

E. Voltage Drop for Selected Conductor Sizes

To ensure compliance and operational efficiency, we model voltage drop across 125 m cable runs for each generation line, using typical conductor sizes:

Selected Conductors:

- Copper: 95 mm²
- Aluminium: 120 mm²

Calculated Voltage Drops:

$$\Delta V_{\text{copper}} = \boxed{13.16\ \text{V}} \quad (\,0.04\%)$$

$$\Delta V_{\text{aluminum}} = \boxed{16.20\ \text{V}} \quad (\,0.05\%)$$

These values fall well below the 5% threshold (~1,500 V), confirming that both configurations are valid. Aluminum offers a cost-effective solution, while copper provides slightly lower resistance and longer lifespan in moist soils.

F. Cell Type for Turbine Interconnection

Based on 6 turbines, split across 2 balanced generation lines (3 turbines each), the recommended interconnection cell is:

$$\boxed{0L + 2V + 1P}$$

Where:

- 0L: Zero loop connection (not a ring)
- 2V: Two vertical links (generation lines)
- 1P: One point of delivery or collection (e.g., central substation cabinet)

This setup:

- Minimizes cable runs
- Balances power flow
- Reduces construction cost

G. VQ Turbine Prototype – 1.5 kW Electrical Current Analysis

For the VQ regenerative wind system, we use six turbines, each delivering 1,500 W into a 48 V DC shared system.

1. Current per Turbine:

$$I = \frac{1,500}{\sqrt{3} \cdot 48} \approx \boxed{18.04\ \text{A}}$$

2. Total System Current:

$$I_{\text{total}} = \frac{9,000}{\sqrt{3} \cdot 48} \approx \boxed{108.25\ \text{A}}$$

This configuration remains below the 150 A threshold for affordable DC infrastructure, and is compatible with:

- MPPT charge controllers (Victron 150/100 or similar)
- Modular lithium or AGM battery banks
- 10–25 mm² solar-grade copper wiring over ≤60 m

This setup balances **power density**, **maintainability**, and **scalability**, making it ideal for early-stage lab and cabin electrification at VQ.

Complete Electrical Sizing for VQ Prototype System

The VQ wind system comprises **six 1.5 kW turbines** (totalling 9 kW) feeding into a **48 V DC microgrid**. Below are the critical sizing calculations.

A. Cable Sizing for 18 A Per Turbine

To keep voltage drop below 3% over a **60 m run**, the required copper conductor section is:

$$\boxed{\geq 23.25\ \text{mm}^2}$$

B. Battery Bank Sizing for 10 kWh Storage

For a 48 V system:

$$\frac{10,000\ \text{Wh}}{48\ \text{V}} = \boxed{208.3\ \text{Ah}}$$

B. Voltage Drop Estimates for Available Cables

Cable Size	Voltage Drop (60 m, 18 A)	% of 48 V
10 mm²	3.35 V	6.98% ⚠️
16 mm²	2.09 V	4.36% ✅

Recommendation: Use ≥25 mm² if 3% target is strict. 16 mm² is acceptable for most real-world installations.

D. Charge Controller Sizing

For 18 A per turbine, using Victron or EPEVER:

- **Victron SmartSolar MPPT 150/35** (up to 35 A, 48 V) – ideal
- 2–3 turbines can share a **Victron 150/70** if needed

E. Inverter Sizing

For 9 kW wind input, a 5–7 kW inverter provides stable AC power:

- **Victron MultiPlus 48/5000** or **Quattro 48/8000**
- Surge handling + smart load balancing
- Pure sine wave output at 220 V

F. DC Protection

- Use **DC fuses or breakers** rated:
  - **25–32 A** per turbine input
  - Main line fuse: **125–150 A**

Alternative Energy Storage Methods (VQ-Friendly)

1. Gravity-Based Storage (Elevated Mass or Weight)

- **Concept:** Use wind to lift a weight (e.g., concrete or stone), then drop it slowly through a generator.
- **Example:** 1-ton weight lifted 10 m stores ~0.027 kWh
- **Pros:** Extremely durable, visual, educational
- **Cons:** Needs structural rigging, not compact

Use case: Tower-integrated lift using windmill torque and flywheel assist

Water-Based Gravity Battery (e.g., Tower Tank or Hillside Flow)

- **Concept:** Pump water uphill; let it flow down through a micro-hydro turbine
- **1,000 L lifted 10 m = ~0.027 kWh**
- Scalable with tanks, elevation
- Works well **with existing hill terrain or towers**

Use case: Rooftop or tree-mounted storage tanks with vertical discharge

3. Flywheel Mechanical Storage

- Concept: Spin a heavy rotor with wind torque; reclaim via generator
- Pros: Durable, instant response, low voltage
- Cons: Friction losses, safety limits at high speed
- Stores 0.05–1 kWh easily at small scale

Use case: Low-speed system tied to VAWT shaft with gearing

4. Thermal Storage (Phase Change or Heated Mass)

- Concept: Convert wind into heat (via resistance or friction), store in:
  - Salt tanks
  - Water drums
  - Brick or sand beds
- Pros: Cheap materials, useful heat output
- Cons: Needs resistive load or heat exchanger

Use case: Heat retention barrels for greenhouses, showers, cooking

5. Compressed Gas + Water Hybrid (Heron's Fountain Loop)

- Wind pumps water + air into sealed tanks
- Triggers a self-sustained gravity and pressure loop
- Regenerates energy through hydraulic head + pneumatic release

Use case: "Pressure well" designs that act like kinetic batteries

6. Saltwater or Carbon-Iron Batteries (Low-tech Chemical)

- DIY, home-built batteries using:
  - Iron, carbon rods, salt brine
  - Supercapacitor-style layers (banana peels, charcoal)
- Low efficiency, but feasible for emergency lighting

Best Hybrid Combo for VQ:

Source	Storage	Delivery
Wind (VAWT)	Flywheel + Air	Air motor → DC gen
Wind (pump)	Elevated water	Micro-hydro release
Wind + PV	Heat → barrel storage	Radiant/cooking water
Wind	Batteries ($LiFePO_4$)	Inverter → AC loads

6. Section 5 – Alisio Sur Case Study and Qatuan Application

The Alisio Sur windfarm in Gran Canaria offers a benchmark in contemporary large-scale windfarm design. It serves as the culminating exercise of the module, requiring students to apply physical, technical, and economic knowledge through simulation tools such as **Windographer** and **WAsP**. By examining its layout, turbine configurations, wind resource evaluation, and electrical infrastructure, we can contextualise the lessons for application in regenerative micro-energy systems like Vila Qatuan.

Alisio Sur Overview:

- **Location:** Gran Canaria, Spain
- **Turbines:** GE153, SG170, or V162 (depending on configuration)
- **Installed capacity:** 42–50 MW
- **Hub height:** 120 m
- **Wind resource:** ~8.0–8.5 m/s mean speed (at 80 m)
- **Terrain:** Complex topography requiring wake optimisation and directional analysis

Simulation Metrics:

- **Weibull Parameters:**
  - A ≈ 8.0 m/s
  - k ≈ 2.1 (moderately stable wind)
- **Turbulence Intensity:** Within IEC Class II standards
- **Capacity Factor (CF):** 42–46% depending on layout and turbine model
- **Wake Loss:** Maintained below 10% with proper spacing (3D x 7D rule)
- **Cable Loads:** Up to 400 A per group of turbines; switchgear selected accordingly

Simulation Tools Applied:

- Windographer for initial data cleaning and profile modelling
- Climate Analyst and WAsP for site synthesis, wake modelling, and yield prediction

VQ Track B Interpretation

While Alisio Sur models a multi-turbine, grid-integrated installation, its simulation approach remains invaluable to Qatuan's regenerative goals. Several key lessons translate directly:

1. Weibull Projections: Even with limited met data, synthesising Weibull parameters allows early-stage yield forecasting. At Qatuan, $A \approx 7.0$ and $k \approx 1.8$ were estimated from terrain type and visual wind patterns, supporting turbine selection.
2. Wake Avoidance: Despite having only one prototype turbine initially, awareness of future cluster planning enables wake-free siting. Qatuan's modular expansion logic avoids interference naturally.
3. Slope and Elevation Considerations: Alisio Sur placed turbines on ridge lines to exploit venturi acceleration. The Qatuan turbine was placed at 794 m with a clear east-west corridor, following this principle at micro-scale.
4. Load and Infrastructure Scaling: Whereas Alisio Sur designs for MV grid export, Qatuan's infrastructure is embedded. Current calculations and cable sizing were still derived using the same equations, scaled down to 1.5 kW.
5. Energy Use Philosophy: Alisio Sur treats energy as a commodity to export. Qatuan treats it as a nutrient — stored, circulated, and directed to purpose. Its micro-energy ecology offers resilience through diversity.

Capacity Factor Estimation – VQ Prototype

To gauge operational performance, we estimate the capacity factor (CF) for the VQ Track B prototype:

CF = Actual Output kWh/year {Rated Power} x 8760

Assumptions:

- Rated Power: 1.5 kW

- Daily Output Estimate: 2.4 kWh

- Annual Output: 876 kWh

CF ≈ {876} {1.5 \times 8760} ≈ 6.7%

While modest, this CF reflects the turbine's primary use in mechanical work and pressure storage, rather than grid-tied electricity export. The system is optimized for reliability, not peak throughput.

Grid Isolation / Anti-Islanding

The Qatuan wind system is designed as a **fully off-grid, isolated architecture**, with no grid export. All future inverter connections will adhere to **anti-islanding protocols** for safety and regulatory compliance.

Conclusion of Comparative Insight

The Alisio Sur case study affirms the value of simulation, spatial logic, and technical forecasting. But Qatuan reinterprets these tools through the lens of place-based stewardship, integrating wind energy not into the grid, but into **daily life** — one pump, one circuit, one module at a time.

It is wind energy not for export, but for embodiment.

7. Conclusion

This report has explored wind energy from both a rigorous academic and applied regenerative perspective. Through five interconnected sections, we progressed from the physical formation of wind to the real-world implementation of wind energy systems. Each theoretical concept from the module — including atmospheric dynamics, turbine technology, micro-siting methods, and electrical infrastructure — has been applied in practice to a living prototype at **Vila Qatuan**, offering a dual validation of the learning outcomes.

The academic case study of **Alisio Sur** demonstrated how large-scale windfarms are optimised for yield, efficiency, and network integration. In contrast, the **Qatuan prototype** translated these principles into a micro-infrastructure model — one that prioritises **resilience over volume**, **adaptation over expansion**, and **sufficiency over surplus**.

By embedding energy into the daily rhythm of rural life, the project honours the spirit of wind energy not as an industrial export product but as a **living relationship between atmosphere, land, and community**.

8. Required Reading and Referenced Materials (Module PDFs)

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La Energía Eólica, Edición Fundación Naturgy. Año 2012

Con el Viento a Favor, Edición Fundación Esteyco. Año 2015

Dominando el Viento, Edición Anemos. Año 2019

Manual del programa WASP – Riso National Laboratory

The Comet Program Publications

Solargis Global Irradiation Atlas, 2013

Atlas Eólico Europeo, DTU, 1990

Danish Wind Industry Association – www.windpower.org

From *WIND TURBINE TECHNOLOGY AND WIND DATA ANALYSIS.pdf*:

Manual del Programa WASP (WASP Program's manual)

Programa Windographer

Vestas – www.vestas.com

Siemens Gamesa – www.siemensgamesa.com

GE Onshore Wind – www.ge.com

Nordex – www.nordex-online.com

Goldwind – www.goldwindglobal.com

Enercon – www.enercon.de

Envision – www.envision-group.com

Shanghai Electric – www.shanghai-electric.com

MySE – www.myse.com.cn

Windey – www.chinawindey.com

Suzlon – www.suzlon.com

Sinovel – www.sinovel.com

Dongfang Electric – www.dec-ltd.cn

CSIC HL Wind Power – www.csic.com.cn

Turbine Manufacturer Index – thewindpower.net

Bloomberg Wind Energy Sector Reports

Cuadernos Técnicos – Plantas Eólicas, ABB

Aerogeneradores Modernos – Pfernandezdiez.es

www.bornay.com

www.solener.com

www.windturbinestar.com

From *MICROSITING STUDY THROUGH AN ELECTR.pdf*:

WAsP Program (Wake and terrain simulation software – DTU/RISO)

From *WINDFARM DESIGN.pdf*:

Principios de Conversión de Energía Eólica, Edición CIEMAT. Año 2009

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Solargis. (2013). *Global Irradiation Atlas*.

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Danish Wind Industry Association. (n.d.). Retrieved from https://www.windpower.org

ABB. (n.d.). *Cuadernos Técnicos – Plantas Eólicas*.

Pfernandezdiez. (n.d.). *Aerogeneradores Modernos*. Retrieved from http://www.pfernandezdiez.es

10. Expanded Technical Evaluation & Integrated Design Reflections

This final section complements the core learning trajectory of the wind energy module by addressing key technical and contextual topics that were either lightly treated or omitted in the primary chapters. Here we provide a dual analysis: aligning with academic best practices (Track A), while also grounding each topic in the applied realities of the Qatuan prototype (Track B). This ensures a comprehensive, critical, and demonstrably expert grasp of the full module landscape.

10.1 Cost Evaluation and Scaling Logics

Track A:
Utility-scale wind projects evaluate financial viability using LCOE, IRR, and NPV models. These account for capital and operational expenditure, yield expectations, financing conditions, and policy incentives.
Typical payback spans 7–12 years.

Track B:
At Vila Qatuan:

- CAPEX: R$7,500–R$12,000 for the turbine system, R$3,000–R$5,000 for pumping, R$2,500 for structures
- OPEX: R$400–R$800/year
- ROI: 4–5 years, based on replacing diesel and manual water-pumping labour

10.2 Operational Control and Local Monitoring Approaches

Track A:
SCADA systems provide full turbine diagnostics and grid communication, enabling predictive maintenance and performance optimisation.

Track B:
Qatuan employs:

- Analog pressure/voltage gauges
- Float switch cut-offs
- Manual clutch toggles
- Arduino + GSM telemetry for basic remote data if required

10.3 Wind Data Logging: From Academic Standard to Field Deployment

Track A:
IEC calls for 10 m masts, 10-minute interval recordings over ≥1 year, with Class 1 sensors and Weibull curve fitting via Windographer or WAsP.

Track B:
Qatuan will use:

- 10 m temporary pole
- Cup anemometer + wind vane
- Logger with SD/LoRa
- 10-min intervals, rotating locations, seasonal shifts for terrain calibration

10.4 Blade Materials, Fabrication and Design Implications

Track A:
Composite blades use fibreglass-reinforced epoxy with NACA-profiled sections, fine-tuned with CFD tools.

Track B:

Qatuan blades will be:

- Laminated pine + fibreglass wrap
- Marine epoxy coating
- Recycled aluminium hubs, steel shafts
- Built for low-speed/high-torque performance and easy repair

10.5 Grid Logic and Microgrid Adaptation

Track A:
Grid-tied systems use 30–60 kV MV feeders, synchronisation units, and transformers. Inverter compliance and export control is mandatory.

Track B:
No export — but prepared for microgrid logic:

- 12–24 V DC use
- Future hybrid inverter (Victron/MPP) for system integration
- "Plug-and-play" turbine expansion via modular bus

10.6 Energy Storage Design: Mechanical and Electrical Options

Track A:
Storage options (Li-ion, lead-acid, flywheels) are judged on kWh, DoD, round-trip efficiency, and longevity.

Track B:
Qatuan prioritises:

- **Water lift energy:** ~8.2 Wh/day
- **Compressed air:** 200–300 L @ 4 bar (≈1 day buffer)
- **Optional battery:** 2 kWh $LiFePO_4$ or 200 Ah lead-acid for lights and backup

Environmental and Social Considerations

The VQ turbine is designed with environmental and community compatibility in mind:

Noise Impact: Operates below 60 dB; low-RPM blades reduce sound propagation.

Wildlife Safety: Blades are low-altitude, painted for visibility, and rotate slowly—minimizing bird strike risk.

Material Ethics: Uses recyclable metals, laminated timber, and minimal electronic waste.

Community Interface: Operable by non-specialists; readable systems; open data integration.

This approach aligns with regenerative design values: reduce, reuse, localize, and educate.

Conclusion to Chapter 10

Each expanded topic affirms Qatuan's embedded, regenerative ethos. While Track A provided tools for analysis, Track B embodies application grounded in terrain, need, and cultural logic. What emerges is not just a wind system — but a **wind culture**: intelligent, modular, and rooted in place.

11. Further Reading and Manufacturer Resources

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GE Onshore Wind. (n.d.). https://www.ge.com/renewableenergy/wind-energy/onshore-wind

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WAsP Software. (n.d.). https://www.wasp.dk

Windographer Software. (n.d.). https://www.mistaya.ca

Appendix F. Thesis Cross-Reference Map

Correspondence between QAIB Application Report Sections and Core Thesis Chapters

QAIB Report Section	Corresponding Thesis Chapter	Purpose / Contribution
Abstract	Chapter 1 – Introduction	Frames the study's practical significance within the broader thesis context of regenerative energy
Section 2 – Physical and Meteorological Concepts	Chapter 3 – Environmental Site Characterization	Provides raw climatic and wind data that underpin site-specific feasibility
Section 3 – Wind Turbine Technology and Performance Analysis	Chapter 4 – Systems Design	Supports theoretical and technical evaluation of turbine configuration and hybrid potential
Section 4 – Micro-siting and Terrain Evaluation	Chapter 5 – Case Study Deployment	Grounds site selection strategy and terrain-informed placement logic for turbine systems
Section 5 – Wind Farm Design and Hybrid Architecture	Chapter 4 – Systems Design	Builds the structural logic for the hybrid model (wind, solar, biogas → compressed air)
Section 6 – The QAIB Pneumatic Hybrid Energy System	Chapter 6 – Design Implementation	Details the core technological mechanism proposed for decentralized rural electrification
Section 7 – System Performance and Pressure Output Metrics	Chapter 7 – Results and Evaluation	Directly supplies practical benchmarks and expected yield ranges under prototype conditions
Section 8 – Alisio Sur vs. VQ Micro-siting Case Study	Chapter 5 – Case Study Deployment	Offers comparative insights that inform conclusions about geographic adaptation and layout logic
Section 11 – Deployment Strategy and Cost Model	Chapter 8 – Implementation Pathways	Demonstrates a replicable, phased approach to scaling regenerative infrastructure
Section 12 – From Wind to Wisdom	Chapter 9 – Education, Open Science and Replication	Supports thesis emphasis on community empowerment, citizen science, and long-term autonomy
Figures 1–4	Various Chapters	Visual references for site layout, system design, pressure model logic, and component integration

Appendix G: Comparative Case Study — Ventisquero Norte Wind Farm (Chile)

This case study was originally developed in May 2025 as part of the *Design and Management of Energy Projects* curriculum. It models the full-cycle development of a 205.8 MW utility-scale wind farm located in Chile's Coquimbo Region, applying ISO 21500 and PMBOK-aligned project planning methodology.

Included here as Appendix G, the project serves as a technical counterpoint to QAIB's regenerative, community-scale design strategy. While the QAIB/VQ model prioritizes autonomy, compressed-air storage, and modular resilience, this industrial case illustrates the contrasting logic of centralized deployment — including milestone-driven funding flows, grid interconnection, and conventional power purchase agreements.

This dual inclusion reflects QAIB's commitment to bridging large-scale energy logic with site-adapted regenerative principles, and offers readers a direct comparison between capital-intensive infrastructure and low-tech, replicable alternatives.