RUNE
RENEWABLE INTELLIGENCE

Rune Wind Workspace Validation Program

Verification & Validation Report

VV-WIND-WORKSPACE-003-2026

Scope: Wake physics, AEP and finance model validation with real park datasets

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Abstract

This report extends Rune Wind Workspace V&V with two additional real-park benchmarks: one offshore case (Amrumbank West) and one onshore case (Sole du Moulin Vieux, SMARTEOLE baseline subset). The goal is maximum-traceability validation, with no synthetic park geometry and no fabricated operational references. The verification chain includes centerline wake checks, farm-level AEP comparison against PyWake and FLORIS, directional error diagnostics, Jensen root-cause isolation, SCADA-linked backcast screening, finance parity checks, and new multi-site real-park tests.

Across the full executed suite (`35 passed, 1 xfailed`), Bastankhah and GCH remain within bankability-grade thresholds in all enforced cases. Jensen now shows strong agreement in offshore and real-park transferability after dynamic-C_t and overlap corrections, with one known residual case in dense-array Lillgrund (10.40 % absolute AEP deviation versus a 10.00 % strict gate).

Contents

1 Nomenclature

Symbol	Definition
U_∞	Free-stream wind speed
D	Rotor diameter
C_t	Thrust coefficient
k_w	Wake expansion coefficient (Jensen/Bastankhah context-specific)
δ	Wake deficit (fractional speed reduction)
$P(v)$	Turbine power curve output at speed v
f_d	Directional frequency (sector probability)
$p_{d,s}$	Wind speed-bin probability in direction d
AEP	Annual Energy Production
nMBE	Normalized Mean Bias Error
nRMSE	Normalized Root Mean Square Error
R^2	Coefficient of determination
CF	Capacity factor

2 Introduction

Rune Wind Workspace contains a production implementation of Jensen, Bastankhah-Gaussian and GCH wake models, with farm-level AEP and financial outputs used in engineering and pre-feasibility workflows. Previous validation rounds established parity on Horns Rev 1 and Lillgrund and identified one persistent Jensen gap in dense-array operation.

This update answers two requirements:

1. Add further validation using real onshore and offshore parks.
2. Produce a complete V&V report with transparent methodology, equations, results and limitations.

3 Methodology

3.1 Verification Philosophy

Validation is split into three layers:

1. **Model-form verification**: centerline and directional behavior against reference model outputs.
2. **Farm-level equivalence**: AEP comparison versus PyWake/FLORIS under matched layouts, curves and sector climates.
3. **Operational plausibility**: SCADA-linked backcast and capacity-factor range checks.

3.2 Core Equations

Farm net AEP is evaluated as:

$$\text{AEP}_{\text{net}} = \sum_{d=1}^{N_d} \sum_{s=1}^{N_s} P\left(v_s \cdot (1 - \delta_{d,s})\right) \cdot f_d \cdot p_{d,s} \cdot 8760 \quad (1)$$

where $\delta_{d,s}$ is the model-dependent wake loss term after superposition and layout interactions.

Relative AEP error against a reference solver is:

$$\epsilon_{\text{rel}}(\%) = 100 \cdot \frac{\text{AEP}_{\text{Rune}} - \text{AEP}_{\text{ref}}}{\text{AEP}_{\text{ref}}} \quad (2)$$

For regression vectors $\mathbf{y}$ (reference) and $\hat{\mathbf{y}}$ (prediction):

$$\text{nMBE} = \frac{\frac{1}{n}\sum_i (\hat{y}_i - y_i)}{\bar{y}}, \quad \text{nRMSE} = \frac{\sqrt{\frac{1}{n}\sum_i (\hat{y}_i - y_i)^2}}{\bar{y}}, \quad R^2 = 1 - \frac{\sum_i (\hat{y}_i - y_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (3)$$

3.3 Datasets and Provenance

Offshore historical benchmarks

- Horns Rev 1 (PyWake example dataset)
- Lillgrund (PyWake example dataset)

Real-park additions in this report

- **Amrumbank West (offshore):** layout and turbine metadata from Open European Offshore Wind Turbine Database (DOI: 10.5281/zenodo.17311571), 2024 wind climate from Open-Meteo hourly archive.
- **Sole du Moulin Vieux / SMARTEOLE (onshore):** SCADA/control/static data from DOI 10.5281/zenodo.7342466; baseline subset with all turbines non-derated and wake-steering inactive.

Derived, compact, traceable inputs are stored in:

- `docs/validations/wind_workspace_vv_2026/data/amrumbank_west_realpark_2024.json`
- `docs/validations/wind_workspace_vv_2026/data/smarteole_baseline_realpark_2020.json`

3.4 Acceptance Thresholds

- **Screening grade**: typically $\leq$ 6–12% absolute AEP error depending on model/site density.
- **Bankability gate**: typically $\leq$ 3–8% absolute AEP error depending on test objective.
- **SCADA backcast gate**: site-dependent thresholds on R^2, nRMSE and annualized energy bias.

4 Calibration and Root-Cause Actions

4.1 Implemented Changes

The following corrections/calibrations are active in production code:

- Jensen dynamic $C_t(v)$ support in AEP integration path.
- Jensen rotor-overlap weighting in pairwise deficit transfer.
- Bastankhah calibration ($k = 0.03$) for improved parity versus reference solvers.
- GCH turbulence mapping and dynamic-C_t consistency adjustments.
- Bastankhah promoted as default wake model in backend/frontend defaults.

4.2 Residual Jensen Dense-Array Case

In Lillgrund-Jensen, absolute error improved from 11.96 % to 10.40 % after overlap weighting (gain: 1.57 percentagepoints), but remains marginally above the strict 10.00 % gate.

5 Results

5.1 Centerline and Classical Offshore Benchmarks

Table 2: GCH centerline verification versus FLORIS reference points

Metric	nMBE (%)	nRMSE (%)	R^2	Max abs err (%)
Rune GCH vs FLORIS curve	2.88	3.14	0.9933	3.80

Table 3: Farm-level AEP error versus PyWake (Horns Rev 1 and Lillgrund)

Case	PyWake (GWh)	Rune (GWh)	Rel. error (%)
Horns Rev 1 – Jensen	701.86	656.60	-6.45
Horns Rev 1 – Bastankhah	654.64	658.58	+0.60
Lillgrund – Jensen	346.56	310.53	-10.40
Lillgrund – Bastankhah	291.36	296.99	+1.93

5.2 FLORIS Farm-Level Cross-Tool (GCH)

Table 4: Rune GCH versus FLORIS AEP

Case	FLORIS (GWh)	Rune (GWh)	Rel. error (%)
Horns Rev 1	673.54	631.41	-6.25
Lillgrund	304.01	283.60	-6.71

5.3 Directional and Dynamic-C_t Diagnostics

Table 5: Directional Jensen mismatch reduction after harmonizing k_w

Site	MAE reduction (%)	RMSE reduction (%)	Corr. (harm.)	MAE harm. (pp)
Horns Rev 1	62.52	49.34	0.9304	3.09
Lillgrund	65.02	63.41	0.9734	3.67

Table 6: Jensen parity after dynamic-C_t activation (vs PyWake $k = 0.04$)

Site	Static err (%)	Dynamic err (%)	Error reduction (%)
Horns Rev 1	3.93	0.79	79.80
Lillgrund	8.09	0.65	91.93

5.4 New Real-Park Validation (Onshore + Offshore)

Table 7: Real-park AEP parity against PyWake

Park	Model	PyWake (GWh)	Rune (GWh)	Rel. error (%)
Amrumbank West (offshore)	Jensen	1387.44	1372.00	-1.11
Amrumbank West (offshore)	Bastankhah	1355.96	1343.31	-0.93
SMARTEOLE baseline (onshore)	Jensen	25.72	25.19	-2.04
SMARTEOLE baseline (onshore)	Bastankhah	25.44	24.44	-3.92

5.5 Financial Model Parity

6 Discussion

The extended benchmark set confirms that current Rune wake/AEP implementations are numerically coherent with market references across multiple geometries and climates. The strongest gains were obtained by removing parameterization mismatches (Jensen k_w and dynamic C_t) rather than by introducing ad-hoc site-specific corrections.

Real-park transferability is supported by low error on Amrumbank West and SMARTEOLE-derived sectors. Offshore parity is especially tight (absolute error ≈ 1.00 %), indicating that the production chain is stable when turbine curve, layout and directional climate are aligned.

The remaining Jensen/Lillgrund residual is concentrated in dense-array wake interaction complexity. Bastankhah remains more robust in this regime and is therefore justified as default model.

7 Limitations

- Lillgrund Jensen strict gate (10.00 %) is still marginally unmet (10.40 %).

Table 8: Capacity-factor plausibility (Rune Bastankhah)

Park	Turbines	Rated power (MW)	Capacity factor
Amrumbank West	80	3.60	0.5325
SMARTEOLE baseline	7	2.05	0.1945

Table 9: Financial validation against NREL 2023 equations

Scenario	Rune LCOE ($/MWh)	NREL LCOE ($/MWh)	Rel. error (%)
Onshore utility-scale	52.03	52.03	5.46×10^{-14}
Offshore fixed-bottom	124.04	124.04	6.87×10^{-14}
Offshore floating	151.15	151.15	3.76×10^{-14}

- Real-park offshore climate uses Open-Meteo reanalysis; this is suitable for model-to-model parity but does not replace full long-term bankable wind resource campaigns.
- SMARTEOLE dataset is filtered to baseline operation (non-derated, steering inactive) to avoid control-induced confounding in baseline wake validation.

8 User-Facing Recommendations

1. Keep **Bastankhah** as default model for production studies and dense layouts.
2. Use **Jensen** for rapid screening, but present directional sensitivity and uncertainty bands when arrays are dense.
3. Use **GCH** for studies requiring yaw/steering sensitivity and higher-fidelity wake-shape behavior.
4. Flag to end users when layout spacing drops below approximately 5D–6D, where model spread typically increases.

9 Conclusion

Rune Wind Workspace now has an expanded, auditable V&V baseline combining classical offshore references, operational onshore checks, and new real onshore/offshore park transferability tests. The current model stack is technically defensible for production use, with Bastankhah as default and GCH available for advanced flow studies. One Jensen dense-array residual remains explicitly tracked and bounded.

References

References

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