



# TWINVEST

Digital Twin for Forecasting of Power Production to Wind Energy Demand

Project title	Universal, open-source and cybersecure Digital Twin to provide investors in onshore wind farms valuable insights about current operations and future investments		
Project acronym	TWINVEST		
Project number	101146936		
Project start date	01/06/2024	Duration	42 months

## D4.4 – INTEGRATED BOTTOM-UP & TOP-DOWN

Due date	31/12/2025	Delivery date	22/12/2025
Work package	WP4 Modelling of individual wind turbine components and design of reliable wind farms		
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Version	V1.0		
Dissemination level	Public		



## VERSION AND AMENDMENTS HISTORY

<b>Version</b>	<b>Date (MM/DD/YYYY)</b>	<b>Created /Amended by</b>	<b>Changes</b>
<b>V0.1</b>	12/12/2025	Dmitrij Mordasov	Review-ready draft.
<b>V0.2</b>	19/12/2025	Dmitrij Mordasov	Review feedback implementation.
<b>V1.0</b>	22/12/2025	Dmitrij Mordasov	Final version.



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## LIST OF ABBREVIATIONS

<b>AEP</b>	Annual energy production
<b>API</b>	Application programming interface
<b>CF</b>	Capacity factor
<b>DT</b>	Digital twin
<b>DX.X</b>	Deliverable X.X
<b>FMI</b>	Functional mock-up interface
<b>FMU</b>	Functional mock-up unit
<b>HSE</b>	Health, safety and environment
<b>IT</b>	Information technology



<b>KPI</b>	Key performance indicator
<b>LCOE</b>	Levelised cost of energy
<b>MAE</b>	Mean absolute error
<b>ML</b>	Machine learning
<b>MPPT</b>	Maximum power point tracking
<b>NTNU</b>	Norwegian University of Science and Technology
<b>O&amp;M</b>	Operation and maintenance
<b>OEM</b>	Original equipment manufacturer
<b>PPA</b>	Power purchase agreement
<b>RCA</b>	Root cause analysis
<b>RMSE</b>	Root mean squared error
<b>R<sup>2</sup></b>	Coefficient of determination
<b>UC</b>	Use case
<b>UI</b>	User interface
<b>US</b>	University of Surrey
<b>WPX.X</b>	Work package X.X



## 1 EXECUTIVE SUMMARY

The TWINVEST project aims to develop a universal, open-source and cybersecure digital twin (DT) framework for onshore wind farms, providing investors and operators with improved insight into both current operations and future investment options. Within this context, *D4.4 Integrated Bottom-up & Top-down* finalises the framework concept for the TWINVEST DT by specifying how the previously developed bottom-up and top-down approaches are combined into a single coherent, stakeholder-oriented framework.

The bottom-up framework from D4.1 by University of Surrey (US) provides a detailed, physics-based representation of a wind farm, built up from component-level wind turbine models to system-level interactions including wakes and grid effects. It is well suited to analysing turbine response to control changes, providing physics-based baselines of turbine behaviour and supporting the study of “what-if” but on its own can be considered relatively computationally intensive and not directly expressed in the key performance indicator (KPI) language used by decision makers.

The top-down framework from D4.2 by Norwegian University of Science and Technology (NTNU), by contrast, is based on operational wind farm data and focuses on harmonised KPI computation, benchmarking and performance monitoring. It delivers a high-level, fast, KPI-oriented view of wind farm performance that aligns with operator and investor needs, but its data-driven approach has limited extrapolation capability beyond the observed operational envelope (requiring external industrial datasets for benchmarking) and offers less detailed view and physical interpretability for root cause analysis (RCA).

D4.4 addresses these complementary limitations by integrating the two frameworks into a single architecture that combines a top-down, KPI-driven view with a bottom-up, physics-based baseline. Building on the DT specifications and use cases defined in D1.1 and D1.2, along with the system architecture in D2.1, this deliverable defines a set of integration objectives and design principles for the TWINVEST DT. Key principles include modularity and loose coupling, separation of concerns and layering, interoperability and openness, explicit data-governance considerations, and extensibility for future models and use cases. The bottom-up models from D4.1 are exposed as Functional Mock-up Units (FMUs) within the model and analytics layer, while the top-down components from D4.2 are implemented as services for data processing, KPI computation, benchmarking and anomaly detection.

The report presents the resulting integrated framework as a five-part structure: 1) A Data Processing Pipeline, 2) a KPI & Metrics Engine, 3) a Performance Baseline Models module, 4) a Benchmarking and Anomaly Detection module and 5) a User Interface and Integration Layer. These modules are embedded and distributed in the layered TWINVEST DT architecture (data, application, User Interface (UI)) and are designed so that new models, KPIs or wind farms can be added by users through configuration and encapsulated interfaces rather than through extensive re-engineering.



To demonstrate the feasibility of the integrated framework, a proof-of-concept prototype has been implemented on an anonymised industrial onshore wind farm case. A dashboard developed by US exposes both farm- and turbine-level views, allowing users to inspect measured KPIs (top-down view), physics-based baseline predictions (bottom-up view) and their integrated combination side by side across multiple temporal resolutions. Visual comparison of time series and aggregated KPIs is complemented by a quantitative assessment based on standard regression metrics between the anonymised supervisory control and data acquisition (SCADA) data and baseline model outputs. Across the analysed periods and indicators, the integrated model achieves improved predictive performance compared to the stand-alone top-down and bottom-up approaches, while preserving the interpretability and KPI focus required by TWINVEST stakeholders.

Validation activities were conducted at three levels: Bottom-up (D4.1) wind turbine model validation, top-down (D4.2) framework validation on wind farm operational data from an industrial partner (D4.2), with these two validation procedures performed by Northel, and an integrated system validation through the dashboard prototype (D4.4). Due to data confidentiality constraints, this public deliverable reports only anonymised results and summarised validation effort conclusions, while detailed numerical validation results remain internal to the project. The prototype is currently limited to historical, offline operation of a single wind farm with a single wind turbine type, but the architectural design and Functional Mock-up Interface (FMI)-based encapsulation are chosen to support future extension, including real-time deployment and integration of additional models from the other TWINVEST work packages.

Overall, D4.4 demonstrates that a modular integration of bottom-up and top-down approaches is technically feasible, fits within the TWINVEST system architecture and provides a natural entry point for specialised models developed elsewhere in the project. The integrated framework constitutes a key step towards a holistic, onshore-focused wind farm DT that can serve both operation decision making and investment analysis.



## 2 INTRODUCTION

### 2.1 Purpose of the Deliverable

D4.4 *Integrated Bottom-up & Top-down* finalises the framework concept for the TWINVEST Digital Twin (DT). It is to provide a publicly accessible description of the method of integrating the previously developed bottom-up and top-down design methodologies of the DT.

### 2.2 Scope and Links to Other Deliverables

The DT framework presented in this document holds an important role in the development of the TWINVEST DT, sitting at the intersection of several earlier TWINVEST activities and forming a bridge to the more implementation-oriented work later in the project. The following, submitted deliverables are linked to this document:

- D1.1 *Digital Twin Specifications*
  - D1.1 specified the overall objectives, functional scope and stakeholder expectations for the TWINVEST DT. D4.4 takes these high-level expectations as a reference and demonstrates how the integrated top-down and bottom-up framework addresses the investor- and operator-oriented requirements identified within.
- D1.2 *Use Cases Requirements Definitions*
  - D1.2 provides detailed use case descriptions of the industrial TWINVEST project partners, including user roles, workflows and information needs. One of these use cases was used to develop and validate both the D4.2 top-down model and the integrated D4.4 model presented within this document. This and the other use cases are also used to derive functional and non-functional requirements of the integrated framework.
- D2.1 *Preliminary Digital Twin System Architecture*
  - D2.1 defines the overall IT and system architecture for the TWINVEST DT, including data flows, integration patterns and deployment considerations. The integrated framework presented in D4.4 is designed to fit within this architecture, specifying how the top-down data-driven and bottom-up physics-based models can be exposed as services and Functional Mock-up Units (FMUs), and connected to the data and User Interface (UI) layers defined in D2.1.
- D4.1 *Framework for Bottom-Up Approach*
  - D4.1 developed a bottom-up framework, aiming to achieve a wind farm state representation built from component-level models up to wind turbine and farm level. In D4.4, this bottom-up framework is treated as the physics-based “engine” of the DT in the baseline performance module within, providing simulated reference behaviour and scenario results that can be comparatively analysed against the data-driven KPI layers.
- D4.2 *Framework for Top-Down Approach and Validation*



- D4.2 defined a top-down framework, based on operational data, key performance indicator (KPI) computation, benchmarking and anomaly detection, along with demonstration and validation on an industrial use case. D4.4 builds directly on this work by specifying and implementing the integration with the bottom-up models from D4.1, and extending the validation from a purely operational data-based view to a comprehensive, physics model-informed assessment.

The content of this deliverable is especially relevant for the more concrete implementation of the TWINVEST DT in later work packages. These deal with advanced modelling, demonstration and validation activities. By clarifying how bottom-up and top-down models are combined and exposed to end users, D4.4 serves as a practical blueprint for these subsequent implementation tasks.

### 2.3 Structure of the Deliverable

The deliverable is structured as follows:

- Section 3, BACKGROUND AND MOTIVATION introduces the TWINVEST DT vision, summarises the relevant state-of-the-art in digital twin frameworks, and briefly recaps the bottom-up and top-down approaches developed in D4.1 and D4.2, along with the rationale for their integration.
- Section 4, INTEGRATION REQUIREMENTS AND DESIGN PRINCIPLES summarises the stakeholder groups and representative use cases relevant to the integrated framework, formulates integration objectives and constraints, and sets out the main design principles and architectural implications that guide the implementation.
- Section 5, INTEGRATED BOTTOM-UP & TOP-DOWN FRAMEWORK describes the high-level architecture of the integrated framework, the data and model interfaces (including the use of the Functional Mock-up Interface (FMI) for model encapsulation), the main operational workflows that are supported in the proof-of-concept prototype and its validation strategy and results.
- Section 6, INTEGRATED FRAMEWORK PROTOTYPE presents the proof-of-concept prototype applied to an anonymised industrial case study used for integrated framework testing and a discussion of the prototype's limitations and future work.
- Section 7, CONCLUSION summarises the main outcomes of the deliverable, highlights current limitations and outlines directions for further work in subsequent TWINVEST work packages.



### 3 BACKGROUND AND MOTIVATION

This section positions the integrated bottom-up and top-down framework within the broader context of digital twin development for wind farms and within the existing TWINVEST work. Section 3.1 briefly recalls the overall TWINVEST DT vision and objectives. Section 3.2 summarises the most relevant state-of-the-art DT and O&M frameworks, to be used as inspiration and stepping stones for the current development efforts. Sections 3.3 and 3.4 then recap the main features of the bottom-up framework developed in D4.1 and the top-down framework defined in D4.2 respectively, focusing on the aspects directly relevant for integration. Finally, Section 3.5 motivates the need to combine these two perspectives and explains how the integrated framework aligns with the use cases and stakeholder expectations identified in earlier TWINVEST deliverables.

#### 3.1 Digital Twin Vision for TWINVEST

The TWINVEST project aims to develop a universal, open-source and cybersecure DT for onshore wind farms, providing investors and operators with improved insight into both current operations and future investment options. The DT is conceived as a system-of-systems that connects data from supervisory control and data acquisition (SCADA), power plant controllers and other monitoring systems with physics-based, hybrid and data-driven models, and exposes the resulting indicators through stakeholder-oriented interfaces. Rather than focusing on a single component or narrow operational function, the TWINVEST DT is intended to offer a coherent view across the asset life cycle, from planning and investment decisions to day-to-day operation and performance assessment.

With this vision, the work in WP4 provides the core modelling building blocks. D4.1 develops a bottom-up, physics-based framework for representing individual wind turbines and their aggregation to farm level from their components, while D4.2 defines a top-down, KPI-oriented framework based on operational data, benchmarking and anomaly detection. The present deliverable, D4.4, focuses on how these two perspectives are integrated into a single framework that can be embedded into the overall TWINVEST DT architecture defined in D2.1, keeping in mind the stakeholders and their needs of D1.1 and D1.2.

#### 3.2 Summary of State of the Art

D4.1 and especially D4.2 include extensive reviews of the state of the art implementations and research of similar digital twin frameworks, both in the industry and academia. Due to the sensitive nature of these mentioned deliverables, this document includes a much-condensed recap of the frameworks which were explored and serve as inspiration for the D4.4 framework implementation in Table 1.



Table 1: Summary of the industry implementations of similar frameworks relevant to the TWINVEST DT.

Name	Description and contribution
<b>ROME0</b>  (1)	<p>“Reliable O&amp;M decision tools and strategies for high LCOE reduction in offshore wind” is a Horizon 2020 EU-backed initiative, which developed an integrated platform for condition-based maintenance and O&amp;M decision making support. It combines SCADA data, condition monitoring systems and hybrid diagnostics with cloud analytics, and provides a web dashboard along with 3D asset visualisation.</p> <p>For TWINVEST DT, ROME0 mainly inspires the O&amp;M-oriented modules, time-series and KPI dashboards, and the idea of linking a high-level KPI view with more detailed asset analysis (and visualisations where possible).</p>
<b>SPARTA</b>  (2) (3) (4)	<p>“System Performance, Availability and Reliability Trend Analysis” – an industry-led offshore benchmarking initiative that collects farm-level KPIs from participating operators and returns anonymised comparisons across similar wind farms. It focuses on availability, production and lost production, reliability and other operational metrics.</p> <p>For TWINVEST DT, SPARTA motivates the benchmarking and peer-comparison aspects of the framework, along with providing and acting as a real-world anchor of most used and desired KPIs for wind farm operators.</p>
<b>OpenOA</b>  (5)	<p>NREL’s “Open source Operational Assessment” framework for wind farm SCADA analysis. Ingests and cleans SCADA time series, then computes KPIs such as long-term corrected annual energy production (AEP), operational wake losses, electrical losses and (experimental) static yaw misalignment, with built-in quantification routines. Supports gap analysis between design metrics (pre-construction) and realised operational performance.</p> <p>For TWINVEST DT, OpenOA provides a reference for a modular operational data pipeline, inspiring the treatment of KPIs, and underlines the importance of uncertainty quantification and explicit treatment of data and model error.</p>
<b>NorthWind DT</b>  (6)	<p>Digital twin work within the Norwegian research centre NorthWind, especially WP4 “Digital Twin &amp; Asset Management”. Includes an onshore descriptive wind farm DT prototype (7) featuring KPI processing, a monitoring and simple 3D asset visualisation UI, hybrid (physics-guided machine learning (ML)-based models.</p> <p>For TWINVEST DT, NorthWind’s DT prototype shows an example of how hybrid models, KPIs and a monitoring dashboard can be combined in a simple descriptive DT prototype.</p>



<b>Others</b>	<p>Several other O&amp;M-oriented tools are relevant as background and potential inspiration for future extensions, particular to offshore applications. Examples include <a href="#">NREL’s WOMBAT</a> (8) (scenario-based O&amp;M cost-benefit analysis), <a href="#">SINTEF’s NOWIcob</a> (offshore life-cycle cost and benefit analysis), <a href="#">DNV’s O2M</a> (offshore O&amp;M operations planning) and <a href="#">ECN/TNO’s OMCE</a> (9) (short-/medium-term O&amp;M cost estimator). These tools mainly focus on logistics, operational strategy optimisation and cost modelling for offshore.</p> <p>These are not to be implemented in the TWINVEST DT but demonstrate the broader O&amp;M considerations and the decision-support system that TWINVEST could potentially interface within future work.</p>
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A notable feature of the reviewed initiatives and literature is that most of them target offshore wind applications and focus strongly on the maintenance aspect of O&M. This emphasis is not surprising – offshore wind farm interventions are significantly more expensive and logistically complex than for onshore, with stricter health, safety and environment (HSE) and access constraints, which has driven a large share of DT and O&M decision-support research towards offshore use cases.

Furthermore, academic literature tends to focus on discussion and treatment of the DT concept on a high, abstract level, mainly considering the capabilities and possible difficulties of developing the technology, with the other side being very-specific DT subsystem implementations, limited in their scope (10) (11) (12) (13).

All of this means that there is a clear gap in holistic, system-of-systems digital twin frameworks for onshore wind farms. TWINVEST explicitly addresses this gap by developing an integrated bottom-up and top-down DT framework tailored to onshore wind farms, with all the problems inherent and predominant in this use case.

### 3.3 Summary of the Bottom-up Approach (D4.1)

The bottom-up approach proposed by US reconstructs wind turbine behaviour by modelling main physical subsystem from first principles and integrating them into a complete turbine simulation. Instead of relying on aggregated empirical curves, this method builds turbine performance from the underlying physics of aerodynamics, mechanics, electrical conversion, and control. The result is a transparent, modular, and physics-driven representation that can be used as a reference for assessment, scenario analysis, and digital twin integration.

At the core of the bottom-up approach is a MATLAB implementation composed of several interconnected subsystem models. Each component model operates independently but is coupled through a shared simulation structure, allowing the full turbine behaviour to emerge from component-level interactions. The model framework consists of seven modules visualised in Figure 1:

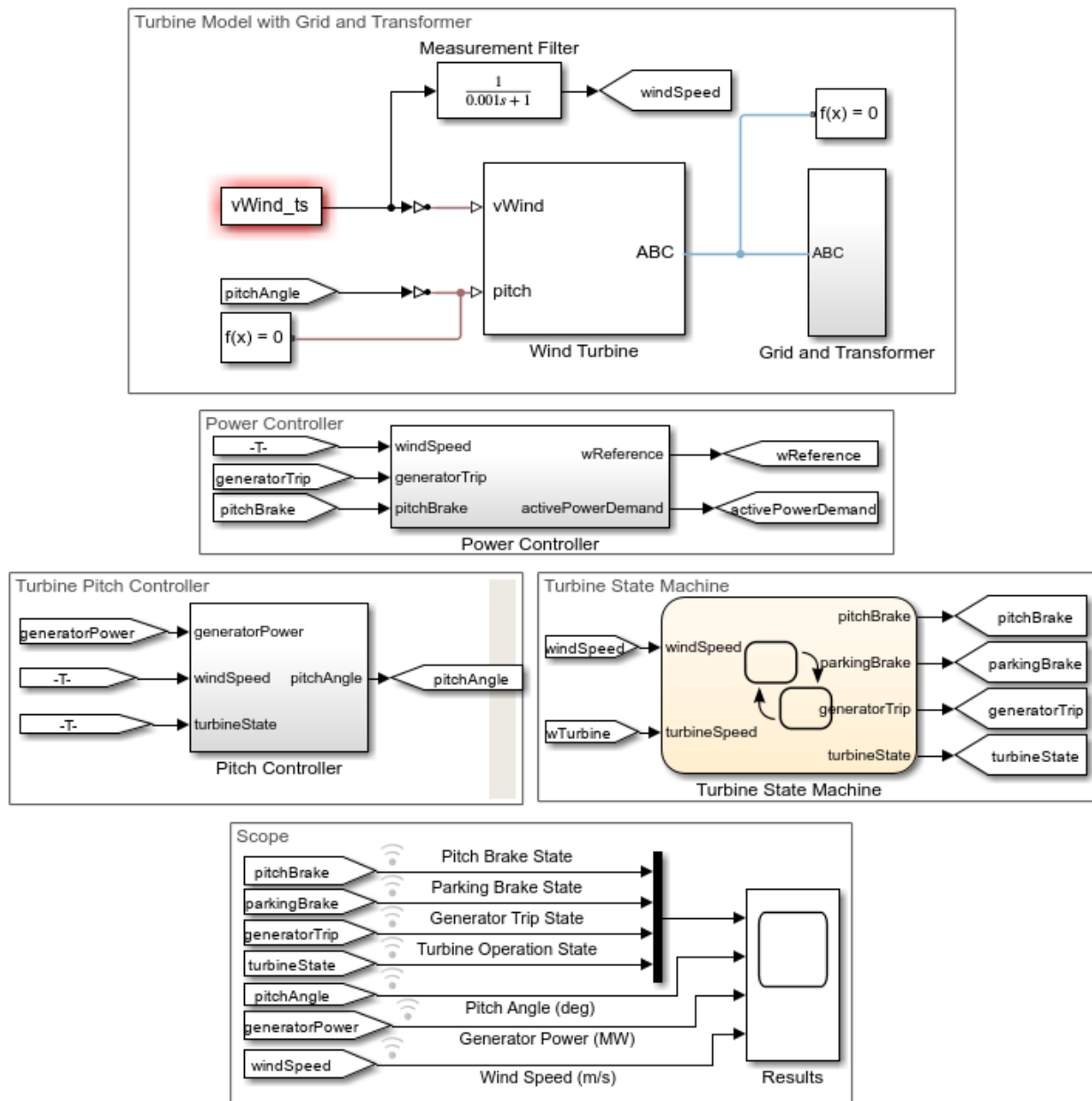


Figure 1: Bottom-up approach model.

**Aerodynamic Subsystem** calculates the mechanical power extracted from the wind using rotor geometry, power coefficient curves, and tip-speed ratio behaviour. It outputs aerodynamic torque and thrust forces, forming the primary physical inputs to the drivetrain and control subsystems. This model captures how wind variability translates into turbine loading and energy production.

1. **Mechanical Drivetrain Subsystem** represents the low-speed and high-speed shafts, gearbox, and rotational inertia. It transforms aerodynamic torque into generator torque through a configurable gearbox model. Parameters such as stiffness, damping, inertia, and gearbox



efficiency determine how the turbine responds dynamically to wind changes and control actions.

2. **Electrical Generator Subsystem** converts mechanical torque into electrical power. It includes generator torque–speed characteristics, conversion efficiency, and power-limiting behaviour. This block ensures that electrical output follows realistic limits such as rated power, torque caps, and cut-in/cut-out operation,
3. **Pitch Controller Subsystem** maintains stability and regulates power by adjusting blade pitch angle. The subsystem includes actuator dynamics, rate limits, and transitions between below-rated and above-rated operation. Proper pitch control enables smooth power regulation under high wind speeds and rapid environmental changes.
4. **Torque Controller Subsystem** governs generator torque to achieve optimal aerodynamic efficiency. In below-rated wind speeds it implements maximum power point tracking, while above-rated it supports power regulation. Its interaction with the drivetrain and aerodynamics is essential for capturing realistic transient and steady-state behaviour.
5. **Operation State Machine** coordinates turbine operating modes which are startup, production, idling, and shutdown. This ensures realistic and safe operation. It governs transitions triggered by wind conditions, grid events, or internal control triggers, allowing the model to simulate how turbines behave under real-world scenarios.

All subsystem models operate within a unified MATLAB Simulink simulation environment that handles data flow, time integration, and scenario configuration. This framework enables detailed time-domain simulations of turbine performance, energy yield, load response, and control behaviour across a wide variety of operating conditions.

Wind farm integration extends this component-based modelling philosophy to multiple turbines by incorporating turbine–turbine wake interactions, farm layout effects, and electrical aggregation. Each turbine model is placed at a defined position in the farm, and wake effects from upstream machines modify the inflow conditions of downstream turbines, influencing power production and loads. The electrical outputs are combined through a simplified internal grid representation that includes cabling and transformer losses. Through these interactions, farm-wide behaviour emerges naturally from individual turbine models, enabling realistic simulation of total energy yield, directional dependency, and operational variability.

### 3.4 Summary of the Top-down Approach (D4.2)

The top-down framework, proposed by NTNU, was developed with the wind farm operator stakeholder in mind (i.e. Energy Generation Companies, Commercial Energy Companies stakeholders in D1.1 *Digital Twin Specifications*). The goal of the framework is to provide the stakeholder with a comprehensive wind farm asset performance overview, enabling a quick ‘top-down’ view. NTNU found it fitting to use a top-down systems engineering design philosophy to design the framework given the stakeholder requirements.



The **integrated** framework proposal consists of five modular parts visualised in Figure 2:

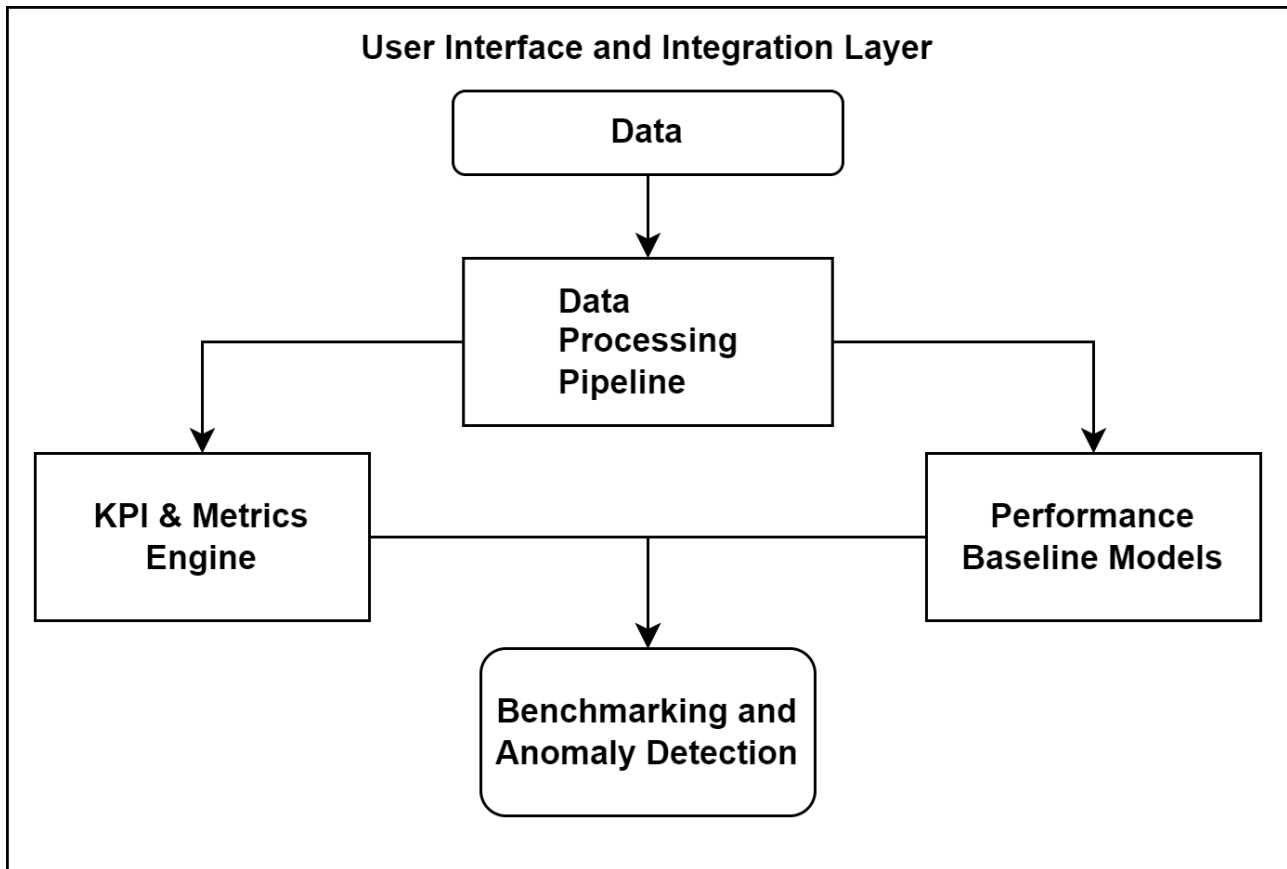


Figure 2: Proposed top-down TWINVEST DT framework modular structure.

1. **Data Processing Pipeline** encompassing data processing, quality control and harmonisation.
2. **KPI & Metrics Engine** computing standardised (and custom) KPIs. This is the heart of the top-down framework and should be considered as the top-down models as per the D4.2 approach.
3. **Performance Baseline Models** benchmarking expected and actual system performance. This module was designed to encompass the bottom-up models, such as the one developed in D4.1, and others developed in other work packages.
4. **Benchmarking and Anomaly Detection** comparatively analysing the KPIs against spatial, temporal and external references.
5. **User Interface and Integration Layer** being the user-oriented, integrating part of this framework, enabling operator access and the use of the modules within their operational workflows.

KPIs in module #2 were recognised as the most intuitive, clear and insight-producing means through which to communicate wind farm performance to its operator, and stand at the heart of the top-down approach to the DT framework.



The other modules were accounted for in the early design phase in order to provide a supporting platform for the KPI engine, without which it would have limited functionality and its results would lack context (and thus some of its value-adding utility in generating insights for decision-making support). Being developed with the end DT in mind, the modular nature stemming from applied systems engineering design practices is based on previous TWINVEST efforts and is modular and customisable enough to fit any future developments of the project (See Section 2.2).

### 3.5 Rationale for Integration

#### 3.5.1 Limitations of Bottom-up Framework in Isolation

The bottom-up framework of D4.1 provides physics-based models. These are high-fidelity representations of a wind turbine from component-level models, combined in order to arrive at a complete wind farm representation accounting for wakes and grid integration. In that context, this framework is particularly valuable for questions such as “How will this turbine respond to a given control change?” and “What are the grid-level implications of this given control strategy?”

While this is essential for investigating the detailed complex aero-servo-elastic behaviour of the wind turbines and for assessing individual wind turbine health and performance, it does not fully meet the stakeholder needs of the DT. In particular, the models require rich input data and expert configuration, on top of being comparatively computationally expensive, and do not, by themselves, easily provide the quick, high-level KPI-oriented dashboard-style view that stakeholders expect in day-to-day operations.

#### 3.5.2 Limitations of Top-down Framework in Isolation

On the other hand, the top-down framework of D4.2 is based on operational data, and is designed to ingest and process SCADA and related measurements in near real-time. It focuses on business and operation-relevant KPIs such as power production, availability, wake and curtailment losses and others that can be quickly and intuitively visualised to provide a quick overview of the wind farm’s state. It is well suited to monitoring performance, benchmarking individual turbines and detecting anomalies from SCADA and related data. Beside a data processing component and some type of calculation of the KPIs, the definitions of which are often given in standards (and tend to be simple equations), the top-down framework is considered much computationally cheaper than the bottom-up one.

However, a purely top-down view has inherent limitations, in that it can help quickly identify that “something is wrong” yet is less able to explain why the deviation occurs, or quantify how alternative operational strategies or “what-if” scenarios would perform. The capacity to extrapolate beyond the operational envelope, provided by its data, is limited without a physics-based reference. Furthermore, the interpretability of purely data-driven models is limited – they are sensitive to data quality and sensor availability issues, any may not provide physically meaningful explanations for detected anomalies or performance changes in purely data-based intra-farm, temporal or external benchmarks.

#### 3.5.3 Complementarity and Added Value of Integration



Integrating the two frameworks addresses these complementary limitations. One side gives depth, the other breadth – integration gives both. By exposing the bottom-up models through orchestrated computational modelling of the wind farm alongside the real-time operational state determination, the DT user can leverage the use of physics-based models. This enables richer benchmarking (e.g. compared to just data-based intra-farm, temporal or external benchmarks) of wind turbines, comparatively analysing the turbine performance to simulated performance under given conditions.

Anomaly detection capabilities based on this comparative analysis of current and simulated performance are also unlocked by this integration of the two frameworks, along with enabling the possibility of running “what-if” scenarios to evaluate operational strategies in the terms of KPIs and other metrics that the stakeholders already use and thus are used to. Root cause analysis (RCA) efforts are made accessible to the user, as a top-down flag in a performance drop can be quickly investigated in depth through the integrated bottom-up detailed representation of the wind turbine asset. In this way, the integrated DT can act both as a diagnostic tool and as an investment decision support tool.

### 3.5.4 Alignment with TWINVEST Use Cases and Objectives

The integrated view is directly aligned with the use cases and stakeholder expectations identified in D1.1 and the system architecture outlined in D2.1. Investors require tools that combine long-term energy yield projections with a transparent view of operational risks and asset degradation. Operators need continuous KPI-based monitoring, but also the ability to test performance optimisation (or downtime mitigation) strategies in a virtual environment before deploying changes on the real wind farm.

By combining the component-level, physics-based models from D4.1 (and other TWINVEST work packages) with the KPI-oriented, data-driven modules from D4.2, D4.4 delivers a coherent framework. This provides a natural entry point for the more specialised models and tools developed in other TWINVEST work packages, ensuring that these contributions can be accessed through a consistent, stakeholder-oriented DT interface.



## 4 INTEGRATION REQUIREMENTS AND DESIGN PRINCIPLES

This section translates the background and motivation of Section 3 into concrete guidance for the design of the integrated TWINVEST DT framework. Section 4.1 reintroduces the main stakeholder groups and generic use cases relevant to the integration of the bottom-up and top-down approaches, and derives a set of integration objectives and constraints from them. Section 4.2 then formulates the key design principles that the framework should follow. Finally, Section 4.3 discusses the architectural implications of these principles and explains how the integrated framework is positioned within the overall system architecture defined in D2.1 and how it interfaces with other TWINVEST DT components.

### 4.1 Stakeholder and Use Case Requirements

Complete stakeholder and requirement analyses are provided in D1.1 and D1.2. This section shows a summary of the aspects relevant to the integration of bottom-up and top-down models.

#### 4.1.1 Stakeholder Overview

It is important to acknowledge that the integration needs of bottom-up and top-down DT frameworks respond to more than one audience, shown in Table 2.

*Table 2: Short overview of the main stakeholders and their concerns regarding the integrated DT framework.*

Stakeholder	Needs
<b>Investors, asset owners</b>	Care about long-term performance of the assets, risks, CAPEX/OPEX trade-offs, investment decision support.
<b>Operators, asset managers</b>	Care about daily performance, O&M strategy optimisation, quick overview of the current wind farm state and health, curtailment and downtime, RCA.
<b>Technical experts, modelling teams</b>	Care about development, implementation and validation of models, doing scenario “what if” studies, not rewriting modules for each single wind farm.
<b>Solution integrators, IT</b>	Care about interfaces, maintainability, scalability, security.

#### 4.1.2 Representative Use Cases

D1.1 and D1.2 contain a multitude of use cases for the TWINVEST DT. Some use cases, representative of the broader set and especially relevant to the framework developed within this deliverable, which are demonstrated in the developed D4.4 proof-of-concept, are shown in Table 3.



Table 3: Representative D4.4 use cases to be demonstrated within the proof-of-concept in this report.

Use Case	Primary Stakeholder	Integration Need
<b>UC 1</b> Assess current wind farm performance	Operators	Needs measured KPIs (top-down) contextualised within the expected performance from physics-based (bottom-up) and other benchmark models.
<b>UC 2</b> Support investment decision for existing wind farm	Operators, investors	Needs long-term AEP and capacity factor (CF) of the wind farm, current power curve of individual wind turbine assets compared to historic and OEM performance specifications.
<b>UC 3</b> Model Validation and Calibration for Predictive Analytics	Data Scientists, Engineers, Asset Managers	Validate bottom-up and top-down models against historical SCADA data using root mean squared error (RMSE), mean absolute error (MAE), and bias metrics. Use the integrated framework to improve prediction accuracy and calibrate model parameters for future energy production forecasting and operational planning.
<b>UC 4</b> Turbine-Specific Performance Optimisation and Load Balancing	Operations Engineers, Control Room Operators	Compare individual turbine power output (T1-T4) across bottom-up simulations and top-down measurements to identify performance variations, optimise turbine-specific control strategies, balance loads across the farm, and maximise overall energy capture by adjusting operational parameters for underperforming units.
<b>UC 5</b> Regulatory Compliance and Performance Reporting	Compliance Officers, Project Managers, Regulatory Bodies	Generate standardised performance reports using integrated framework results that combine physics-based expectations (bottom-up) with actual measured performance (top-down normalised SCADA) to demonstrate regulatory compliance, validate power purchase agreement (PPA) commitments, and provide transparent documentation of wind farm operational performance for stakeholders and authorities.



### 4.1.3 Integration Objectives

While there are functional requirements that can be derived and adapted from D1.1 and D1.2, the definition of functional systems engineering requirements, if not done very carefully at this stage, may easily drift into solution space and thus remove some implementation freedom in the future work packages. So as not to hinder the future work packages through a restrictive formal definition, and assuming the awareness of systems engineering design methodologies, this document refrains from setting concrete requirements for the framework’s integration scope. What follows is a definition of a set of design principles from previously defined functional and non-functional requirements instead.

Building on the DT specifications and use case analysis in D1.1, D1.2 and D2.1, the integrated bottom-up and top-down framework is intended to:

- Provide a comprehensive view of wind farm performance in which SCADA data-driven KPIs and metrics can be compared against baseline models for farm-, turbine- and component level analysis.
- Support both historical and exploratory “what-if” scenarios, with results expressed in the same KPI language chosen by the user for operational reporting.
- Facilitate anomaly detection and RCA efforts by allowing users to move from high-level KPIs and metrics to more detailed, model-based views of asset behaviours at lower levels.
- Allow reuse of the integration patterns (data flow, interfaces) across different wind farm and DT configurations.

### 4.1.4 Constraints and Assumptions of the Framework

The implementation of the framework in later work packages can be facilitated by information on what the framework (and the DT overall) is intended to be through the definition of its objectives, as in the previous Section 4.1.3. The scope of this document is restricted to the integration of the proposed methodologies to be used in the development of the final DT. Thus, some constraints and assumptions regarding D4.4 (not the project overall) must be kept in mind:

- The framework targets onshore wind farms for the present TWINVEST project; offshore applications and the related logistics-driven O&M optimisation, KPIs and other considerations remain out of scope for the project’s time being, yet the framework is made with the option to accommodate this in post-project extensions.
- The current prototype operates on historical SCADA and related data for purposes of demonstrating its feasibility. The integration patterns and data flows described in this deliverable are defined so that a future real-time prototype implementation can reuse them without major redesign.
- Industrial data used for validation are subject to confidentiality constraints in this publicly available report; D4.4 therefore focuses on describing the methodology. Detailed numerical



validation that is performed and documented internally with project partners is not reported here due to confidentiality constraints.

- The integration framework assumes reuse and orchestration of existing models and tools developed in D4.1 and D4.2, rather than the development of entirely new DT components within D4.4 itself.

## 4.2 Design Principles

### 4.2.1 Modularity and Loose Coupling

The TWINVEST DT is designed as a set of loosely coupled modules, so that the bottom-up models from D4.1 (Performance Baseline Models) and the top-down components from D4.2 (KPI & Metrics Engine) can evolve and be reused independently. A small set of core modules provides the most common KPIs, metrics and workflows expected by typical stakeholders, while additional models or functional blocks can be attached as optional modules rather than as hard-coded extensions.

There may be large variations in the sizes, compositions and needs of different wind farms. Not all wind farm operators have the same data management policies, sensor implementations, or reporting policies, along with the variation in SCADA systems of different wind turbine original equipment manufacturers (OEMs). Thus, different users will be able to provide more or less data to the DT. If a user has more data than the most common cases, they should be allowed to utilise their data, which is best enabled through the option for the user to add additional models or simple functional modules. Loose coupling via well-defined interfaces (i.e. FMI) ensures that adding or replacing modules does not require redesigning the overall framework, which is defined here as flexible enough as to accommodate a wide range of additions.

### 4.2.2 Separation of Concerns and Layering

To keep the integrated framework understandable and maintainable, different responsibilities are separated into distinct layers. Each framework layer has a clear role and interacts with adjacent layers through defined data structures and interfaces. For a review of these five modules and their roles, see the summarising Section 3.4 or more detailed Section 5.1.

### 4.2.3 Interoperability and Openness

The framework should be interoperable with a range of modelling tools, programming languages and data sources, and thus not force its users into a single technology stack. To support this, the integration design favours standardised and documented data structures and technology-agnostic interfaces for model coupling and simulation orchestration. These architectural considerations, developed in D2.1, are all taken into account within this integrated framework. This approach is to allow for models developed in other TWINVEST work packages or by external partners to be integrated without major architectural changes, and supports future extensions beyond the project prototype and into operational deployments.



#### 4.2.4 Data Governance and Sensitivity

Industrial data used within the TWINVEST DT can be commercially sensitive, so data governance and confidentiality are treated as first-class design concerns. The possible benchmarking of the user's assets against data of other TWINVEST DT users and general industry figures should not pose the risk of leaking sensitive partner information. Thus, certain data anonymisation and cybersecurity measures shall be taken into account for the presentation of this benchmarking information, making sure that the external interfaces receive only the non-sensitive, treated data.

In practice, this means that raw SCADA and contract-specific information remain confined to trusted environments, while the integration framework focuses on exchanging and presenting derived KPIs, anonymised benchmarks and other processed outputs. For the prototypes within the TWINVEST project, detailed numerical validation can still be (and is being) performed with project partners, but public deliverables such as this D4.4 can only report aggregated or normalised, anonymised results.

#### 4.2.5 Extensibility and Evolvability

The integrated framework is expected to evolve over time as new models, KPIs and use cases are developed in TWINVEST and beyond. To accommodate this, the design aims for extensibility – new baseline models (from physics-based models, fully data-driven models or emerging hybrid physics-guided data-driven models which may ingest DT data streams during training and updating) or KPI definitions should be addable as “plug-ins” or configuration changes, rather than requiring major restructuring of the framework. Similarly, adding a new wind farm should mainly involve setting up the data providing interfaces, metadata and configuration, not rewriting any analysis logic. This evolvability and “plug-and-play” nature of the DT is essential if the framework is to remain useful beyond its initial prototyping and see use in the industry or research.

### 4.3 Architectural Implications

The integrated framework described in this deliverable is designed to fit into the preliminary TWINVEST system architecture proposed in D2.1 (rather than redefining it). This section thus highlights the main architectural implications of combining the bottom-up (D4.1) and top-down (D4.2) approaches, with a focus on model exposure, data flows and their interaction with the TWINVEST data and UI layers.

#### 4.3.1 Position Within the DT Architecture

In the layered architecture proposed in D2.1, the TWINVEST DT is organised into:

- A **data layer**, responsible for ingesting, storing, and providing access to operational and contextual data. In the TWINVEST DT, this includes the **Model/Asset Repository** and the **Scenario Repository**, which underpin data persistence and retrieval for digital twin services.
- An **application layer**, responsible for delivering the core digital twin capabilities and orchestration logic. In the TWINVEST DT, this comprises the **core services**, including **asset**



**management, scenario building, simulation, and co-simulation services**, which consume data from the repositories and execute the required workflows.

- **A user interface (UI) layer**, responsible for exposing digital twin outputs and interactions to end users and stakeholders. In the TWINVEST DT, this includes the **web client, mobile client, and 3D visualisation** components, enabling dashboards, interactive visualisations, and user-driven access to application functions.

The integrated bottom-up and top-down framework primarily resides in the Application Layer, with results exposed through the User Interface (UI). The top-down components (Data Processing, KPI & Metrics Engine, Benchmarking, and Anomaly Detection) are implemented as core digital twin services within the Application Layer. These services consume operational and contextual inputs from the Data Layer (Model/Asset Repository and Scenario Repository) and provide KPI time series and derived indicators to the UI (web client, mobile client, and 3D visualisation).

The bottom-up models from D4.1 are treated as baseline performance engines within the same Application Layer. They can be invoked by the top-down services when simulated reference behaviour is required (e.g., for benchmarking, expected-performance baselines, or anomaly detection). From an architectural perspective, the main implication is that the “integrated framework” should be viewed as a mindset of structuring the engineering analytical process, along with a set of coordinated services and FMUs that plug into the existing TWINVEST architecture, rather than a separate monolithic application.

#### 4.3.2 Exposure of models via FMI and services

D2.1 recommends the use of standards such as the FMI to encapsulate simulation models and enable tool-independent coupling. Following this recommendation, the bottom-up models developed in D4.1 are intended to be exported as FMUs and executed via an orchestration component in the model and analytics layer.

Architecturally, this implies that:

- The Performance Baseline Models module in framework interacts with bottom-up models through FMI-compatible interfaces, rather than direct, tool-specific calls.
- Both physics-based models (e.g. wind farm and turbine simulations) and, where appropriate, hybrid or data-driven models can be wrapped as FMUs or service endpoints with clearly defined inputs and outputs.
- The TWINVEST DT runtime can replace, upgrade or extend individual models (e.g. substitute a simplified farm model with a more advanced one) with minimal impact on the rest of the system, as long as the FMI methodology is preserved.

Similarly, the top-down components (KPI & Metrics Engine, benchmarking services) are exposed as callable services with documented APIs. This allows the user interface (e.g. dashboards developed in



later work packages) to request KPI computations, baseline comparisons or “what-if” scenarios without needing to know the internal implementation details of the models.

#### 4.3.3 Data Flows and Orchestration Between the Bottom-up and Top-down

The integration of the two frameworks has direct implications for data flows:

- Operational data path (top-down): SCADA and related measurements are ingested into the data layer, processed by the Data Processing Pipeline, and passed to the KPI & Metrics Engine to compute KPIs and metrics for dashboards and reporting.
- Baseline and scenario path (bottom-up): When a baseline or a “what-if” scenario is requested, the same data (or user-defined scenario parameters) are passed to the bottom-up FMUs, which return simulated outputs (e.g. active power, loads, AEP/CF) for the specified conditions.
- Comparison and anomaly detection path: The Benchmarking and Anomaly Detection module combines the measured KPIs and model-based predictions, producing comparative indicators (e.g. deviation from baseline, loss breakdowns) that are then forwarded to the UI.

In practice, this implies that the architecture must support:

- Synchronised access to historical (and eventually real-time) data for both KPI computation and model input.
- An orchestrator or workflow layer that can coordinate multi-step operations such as “Compute KPIs -> run relevant FMUs -> aggregate and return KPI-level comparisons”.
- Clear configuration mechanisms and ontology so that adding a new wind farm or a new baseline model mainly involves configuring data mappings, FMUs and KPI definitions, rather than changing core code.

These data-flow implications are reflected in the proof-of-concept implementation presented in Section 5, where the integrated dashboard calls both KPI services and baseline models to populate the visualisations.

#### 4.3.4 Deployment and Scalability Considerations

The architectural decisions described above also affect deployment. Since the integrated framework is expressed as a set of services and FMUs, it can be deployed in a distributed fashion, with KPI computation and model execution components scaled independently according to the computational expenses. For example, KPI services and anomaly detection can be scaled to support multiple wind farms, while computationally heavier, physics-modelled FMU-based simulations can be run on dedicated compute edge nodes or triggered on demand for specific analyses.



## 5 INTEGRATED BOTTOM-UP & TOP-DOWN FRAMEWORK

This section describes how the integrated bottom-up and top-down framework is designed in the context of the TWINVEST DT. Section 5.1 presents the high-level architecture of the integrated framework and its position within the layered system architecture defined in D2.1. Section 5.2 then describes the main data and model interfaces, including the use of FMI for encapsulating bottom-up models and the service interfaces for the top-down components. Section 5.3 illustrates how these building blocks supports representative operational workflows for different TWINVEST DT stakeholder groups, using the generic use cases introduced in Section 4. Finally, Section 5.4 outlines the validation strategy for the integrated framework, linking the bottom-up and top-down validation efforts from D4.1 and D4.2 to the proof-of-concept implementation presented in this deliverable.

### 5.1 High-Level Architecture

The TWINVEST digital twin framework brings together two complementary views of the wind farm: a top-down, data-driven view based on operational KPIs, and a bottom-up, physics-based view based on detailed turbine and farm models. In order to use both consistently for analysis and decision-making, they are embedded in a common system architecture that defines how data are collected, how models are executed and how results are exposed to end users.

This section describes the overall architecture adopted for integrating the top-down and bottom-up models. It explains how information flows from the data sources through the different FMUs, how measured and simulated KPIs are generated and compared, and how the combined results are finally presented in the TWINVEST DT dashboard and APIs.

The integrated bottom-up and top-down framework is embedded in the layered TWINVEST system architecture defined in D2.1, Figure 3 summarises the integrated top-down and bottom-up framework architecture used in D4.4. The design is organised in three layers: Data, Model & Analytics Layer and Application & UI Layer, equivalent to the Data/Application/UI layers proposed in D2.1.

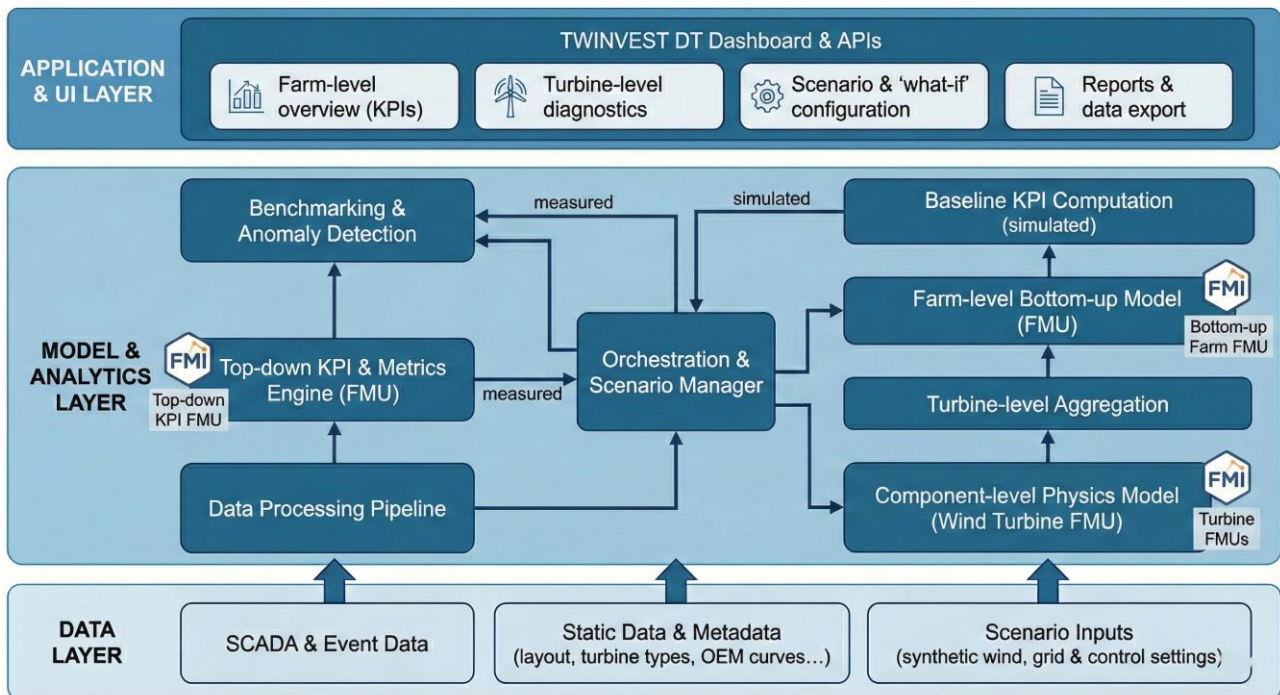


Figure 3: Integrated bottom-up and top-down framework architecture.

At the bottom, the Data Layer provides the inputs that drive both modelling approaches:

- **SCADA & Event Data** (time series) supply measured turbine-level quantities such as power, wind speed, status codes and alarms.
- **Static Data & Metadata** provide the relatively slowly varying information such as farm layout, turbine types, nameplate ratings and OEM power curves.
- **Scenario Inputs** define synthetic wind conditions and grid / control settings that are used for “what-if” simulations.

In the Model & Analytics Layer, these data feed two complementary modelling paths that are both exposed as FMUs and orchestrated in a uniform way.

Top-down framework architecture, SCADA & Event Data first pass through the Data Processing Pipeline, where they are cleaned, validated and mapped to a canonical internal schema. The processed time series are then consumed by the Top-down KPI & Metrics Engine (FMU), which computes farm and turbine-level KPIs (energy production, capacity factor, availability, loss breakdowns, etc.). The resulting measured KPIs form the reference performance indicators derived directly from operational data. These measured KPIs are passed to the Orchestration & Scenario Manager and then to the Benchmarking & Anomaly Detection module, as indicated by the “measured” arrows in the diagram.



Bottom-up framework architecture, static turbine and farm information together with scenario inputs drive a chain of physics-based models. At the lowest level, a Component-level Physics Model (Wind Turbine FMU) represents an individual turbine, including aerodynamics, drivetrain, generator and control. Multiple turbine FMU instances are combined in the Turbine-level Aggregation block and then assembled into a Farm-level Bottom-up Model (FMU) that represents the whole farm. The Orchestration & Scenario Manager configures and runs these FMUs for selected historical or hypothetical scenarios. Their outputs are then post-processed in the Baseline KPI Computation (simulated) block into the same KPI structure as the top-down engine, yielding simulated baseline or scenario KPIs.

The Benchmarking & Anomaly Detection block forms the main integration point between the two modelling paths. It compares measured KPIs from the top-down FMU with simulated KPIs from the Baseline KPI Computation under the same boundary conditions. Systematic deviations are translated into anomaly flags, under-performance indicators or loss estimates. Both measured and simulated KPIs, together with the resulting benchmarking outputs, are finally exposed to the Application & UI Layer.

At the top, the Application & UI Layer is represented by the TWINVEST DT Dashboard & APIs. It offers different views tailored to the main stakeholder groups:

- **Farm-level overview (KPIs)** for operators and investors,
- **Turbine-level diagnostics** for more detailed technical analysis,
- **Scenario & “what-if” configuration** to define and launch simulations via the Orchestration & Scenario Manager
- **Reports & data export** for downstream use in asset management and reporting tools.

Although the underlying implementations differ (data-driven top-down model versus physics-based bottom-up model), the user interacts with a single dashboard that presents a consistent KPI view of the wind farm which is demonstrated in Section 6.

## 5.2 Data and Model Interfaces

To support this architecture, this deliverable defines a small set of data and model interfaces that are shared by the top-down and bottom-up branches and are directly reflected in Figure 3.

### 5.2.1 Data Layer Interfaces

The three data blocks in the Data Layer correspond to three main interface categories:

- **SCADA & Event Data**
  - **Inputs:** time-stamped measurements at turbine and farm level (active / reactive power, wind speed, rotor speed, status codes, alarms, curtailment flags, etc.).



- **Primary consumer:** Data Processing Pipeline, which applies quality control, resampling and signal harmonisation before forwarding the cleaned data to the Top-down KPI & Metrics Engine (FMU).
- **Secondary use:** selected signals (e.g. historical wind and grid conditions) can optionally be replayed as boundary conditions for the bottom-up simulations.
- **Static Data & Metadata**
  - **Inputs:** farm layout, turbine identifiers and types, OEM power curves, cut-in/cut-out speeds, nameplate ratings and other slowly varying configuration parameters.
  - **Consumers:**
    - Top-down KPI & Metrics Engine, which uses them for normalisation (e.g. capacity factor) and loss categorisation, and
    - Orchestration & Scenario Manager and bottom-up FMUs, which use them to parameterise the turbine and farm models and to map asset IDs between SCADA and simulations.
- **Scenario Inputs (synthetic wind, grid & control settings)**
  - **Inputs:** user-defined or externally generated inflow time series, alternative derating and curtailment strategies, maintenance schedules, or grid set-points.
  - **Consumers:** Orchestration & Scenario Manager, which injects these inputs into the component-level turbine FMUs and into the Farm-level Bottom-up Model to produce simulated scenarios for baseline KPI computation.

All data interfaces are time-aligned and keyed by consistent asset identifiers so that outputs from the different modules can be compared and combined without ambiguity.

### 5.2.2 Model Interfaces and Orchestration

In the Model & Analytics Layer, all core models are encapsulated as FMUs following the FMI standard:

- **Top-down KPI & Metrics Engine (FMU)**
  - **Inputs:** processed SCADA & Event Data plus relevant Static Data & Metadata and configuration options (KPI definitions, thresholds, filters).
  - **Outputs:** time-series and aggregated measured KPIs at farm and turbine level, exposed through a generic KPI interface.
- **Component-level Physics Model (Wind Turbine FMUs)**
  - **Inputs:** wind and grid conditions, scenario inputs, static turbine parameters and high-level control commands.
  - **Outputs:** turbine-level electrical power and selected internal states, which are forwarded to Turbine-level Aggregation.
- **Farm-level Bottom-up Model (FMU)**
  - **Inputs:** aggregated turbine outputs, internal grid representation and site-level scenario inputs.



- **Outputs:** farm-level power and other variables required by the Baseline KPI Computation (simulated) block.

The Orchestration & Scenario Manager drives all of these FMUs using a common pattern: instantiate FMU instances, set static parameters, feed time-series inputs, advance the simulation and retrieve outputs. For historical analyses it can replay measured conditions; for “what-if” studies it runs the FMUs under synthetic scenarios. The Baseline KPI Computation converts the resulting bottom-up outputs into simulated KPIs that are structurally identical to the measured KPIs produced by the top-down FMU.

### 5.2.3 KPI Comparison and Outputs

Both KPI streams are finally consumed by the Benchmarking & Anomaly Detection block. This module implements comparison between measured and simulated KPIs (e.g. relative deviations in energy yield or availability), detection of persistent or sudden under-performance at farm or turbine level, and generation of anomaly flags and loss indicators.

The outputs of this block are published through the TWINVEST DT Dashboard & APIs to the farm-level, turbine-level, scenario and reporting views in the Application & UI Layer. Because both the top-down and bottom-up branches adhere to the same KPI interface, new models, KPIs or data sources can be added in future without changing the overall architecture shown in Figure 3.

## 5.3 Operational Workflows

The integrated bottom-up and top-down framework is ultimately intended to support concrete operational workflows for the main TWINVEST stakeholders, rather than remaining a purely conceptual architecture. This section therefore illustrates how the modules described above work together in practice for representative use cases, drawn from the user stories and use cases in D1.1 and D1.2 and summarised in Table 3 of Section 4.1.2.

The workflows are described from the perspective of a user interacting with a dashboard based on the D4.4 prototype implementation. The exact visual design, layout and code implementation of the dashboard are implementation-specific and thus may vary, with the demonstration of the proof-of-concept available in Section 5. Here, the focus is on the sequence of steps and the interplay between the data-driven (top-down) and model-based (bottom-up) components.

### 5.3.1 UC 1 – Assess Current Wind Farm Performance

*As an operator, I want a quick overview of how my wind farm is performing today, so that I can detect underperformance and decide whether any action is needed.*

1. **Select wind farm and time horizon** – The operator logs into the DT dashboard and selects the wind farm of interest and a relevant time range (e.g. last 24 hours, last week, month...) This selection is



passed to the Data Processing Pipeline, which retrieves and harmonises the corresponding SCADA and related data (or retrieves already processed data).

2. **Compute and display KPIs (top-down)** – The KPI & Metrics Engine automatically computes key performance indicators for the selected period (e.g. active power, capacity factor, availability) at farm and turbine level. The dashboard presents these KPIs in tables/time-series plots/simple summary.
3. **Request baseline comparison (bottom-up)** – For the same period, the operator can request baseline performance estimates from the Performance Baseline Models module. This involves running the bottom-up model FMUs (from D4.1 or other TWINVEST DT work packages, for example) for representative operating conditions, and expressing their outputs in the same KPIs as the SCADA and related data (using the input from Step 1. into these baseline models if required).
4. **Benchmark and flag anomalies** – The Benchmarking and Anomaly Detection module compares measured KPIs against the baseline and simple internal benchmarks, such as anonymised industry values for similar wind farms. Turbines or time periods that deviate beyond operator-configurable thresholds are highlighted in the dashboard, and brought to the attention of the user (e.g. as a notification).
5. **Drill-down to detailed views** – From the high-level view, the operator can drill down into a specific turbine or time window (e.g. where underperformance or an anomaly is highlighted). The DT displays both measured series and baseline outputs side by side, enabling quick inspection of whether deviations are likely related to inflow changes, curtailment, or turbine-specific issues. Where bottom-up models provide more detailed variables (e.g. load estimations, forecasted energy production), these can be selectively exposed to support further analysis, and more computationally heavy and detailed simulations on the necessary levels (turbine, component) can be chosen to be executed by the user to assist in RCA efforts.

### 5.3.2 UC 2 – Support Investment Decision for an Existing Wind Farm

*As an investor or asset owner, I want to understand the long-term performance and degradation of an existing wind farm, so that I can decide whether to extend, repower or divest the asset.*

1. **Configure long-term analysis window** – The user selects a multi-year period (e.g. last 5 years) of SCADA data to be retrieved by the Data Processing Pipeline and, where available, a design or OEM reference power curve (present in the Performance Baseline Models).
2. **Assess historical KPIs and trends (top-down)** – The KPI & Metrics Engine computes the long-term KPIs such as annual energy production (AEP), capacity factor (CF), availability, failure rates and other yearly metrics for the given periods. The dashboards presented trends over time at farm and turbine level, with simple statistical summaries.
3. **Derive baseline (bottom-up) and industry benchmarks** – Using the Performance Baseline Models, the integrated framework provides estimates of expected AEP/CF and power curves under healthy wind farm asset conditions, based on physics-based, hybrid or data-driven models



calibrated for the site. These baseline KPIs are compared against the measured values, highlighting systematic underperformance or degradation trends.

4. **Explore scenarios** – Within the DT, the user can explore “what-if” scenarios by running FMUs to simulate the expected performance of the wind turbines given the current trends and their status according to data retrieved in Step 1. Baseline model parameters can be changed, and the sensitivity of the overall performance compared to these adjusted key assumptions (e.g. availability targets, curtailment and maintenance strategies, repowering) with the recomputed predicted KPIs. The resulting changes in these KPIs are presented alongside historical performance, putting the predictions into context and giving a first indication of the potential benefit of different strategies. While more detailed financial analysis remains out of the scope of this current design, KPIs important for insights with regards to investment decisions can be either exported for external analysis, added by the user or in post-project expansion of the DT.
5. **Summarise strategy, save and export as report** – The dashboard can produce a concise summary view and reports, along with data exports, combining the historical KPI trends, benchmarks of baseline vs measured performance and the simple scenario/sensitivity study outcomes of Step 4. This provides a transparent, engineering data-informed starting point for more detailed, project-specific investment analysis.

### 5.3.3 UC 3 – Model Validation and Calibration for Predictive Analytics

*As a data scientist or engineer, I want to validate and calibrate physics-based (bottom-up) and data-driven (top-down) models against historical SCADA data, so that I can improve prediction accuracy, calibrate model parameters, and enhance the integrated framework for reliable future energy production forecasting and operational planning.*

1. **Load historical validation dataset** – The user selects a validation period (typically one or more years) and retrieves SCADA data through the Data Processing Pipeline. The dashboard loads both bottom-up simulation results and top-down model predictions for the selected timeframe, ensuring data consistency.
2. **Compute validation metrics across models** – The KPI & Metrics Engine calculates comprehensive validation metrics (RMSE, MAE, bias,  $R^2$ , correlation) comparing each model's predictions against SCADA measurements. The dashboard displays these metrics at both farm-level and individual turbine-level, showing performance breakdowns for bottom-up, top-down, and integrated framework models.
3. **Visualise model performance and identify systematic errors** – The dashboard presents time-series comparisons showing simulated vs measured power output for each model type, highlighting periods of good agreement and systematic deviations. Bar charts display AEP and capacity factor comparisons, while detailed metrics panels show which turbines and time periods exhibit the largest prediction errors, helping identify model weaknesses.
4. **Analyse error patterns and root causes** – Engineers examine error distributions, temporal patterns, and correlations with operational conditions (wind speed, rotor speed, pitch angle) to



understand why models deviate from measurements. The integrated framework helps identify whether errors stem from physics model limitations (bottom-up), data quality issues (top-down), or integration methodology problems, guiding calibration priorities.

5. **Calibrate model parameters and validate improvements** – Using insights from error analysis, engineers adjust model parameters (e.g., power curves, efficiency factors, degradation rates) and re-run validations. The dashboard tracks calibration iterations, showing improvements in validation metrics and comparing updated predictions against both calibration and hold-out validation datasets. The integrated framework weights are optimised to minimise overall prediction error while maintaining physical consistency.
6. **Document calibration results and export for deployment** – The dashboard generates calibration reports documenting baseline performance, identified issues, parameter adjustments, and final validation metrics. Calibrated model parameters and validation results are exported for use in production forecasting systems, ensuring validated models are deployed with documented performance characteristics and uncertainty bounds for operational planning and decision-making.

#### 5.3.4 UC 4 – Turbine-Specific Performance Optimisation and Load Balancing

*As an operations engineer or control room operator, I want to identify and optimise individual turbine performance variations across the wind farm, so that I can balance loads, maximise energy capture, and prevent premature wear on specific assets.*

1. **Select analysis timeframe and turbine focus** – The user selects a specific period (daily, weekly, monthly, or yearly) and chooses to view individual turbine performance or compare all turbines simultaneously. The dashboard retrieves SCADA data for the selected period through the Data Processing Pipeline.
2. **Compare turbine performance across models** – The dashboard displays power output time series for each turbine, showing bottom-up (physics-based) simulations, top-down (data-driven) measurements, and the integrated framework results. Individual turbine cards show key metrics (MAE, RMSE, bias) comparing simulated vs measured performance, highlighting which turbines deviate from expected behaviour.
3. **Identify performance anomalies and patterns** – The KPI & Metrics Engine calculates turbine-specific performance metrics and visualises them in the charts panel. Operators can identify turbines with consistently lower power output, higher error rates, or unusual patterns compared to the farm average. The dashboard highlights turbines where measured power significantly deviates from bottom-up predictions, indicating potential issues.
4. **Analyse root causes and optimisation opportunities** – By examining wind speed, rotor speed, and pitch angle data alongside power output, operators can identify whether performance issues stem from environmental factors (wind speed variations), operational parameters (yaw, pitch or rotational speed control), or potential mechanical issues. The integrated framework



helps contextualise whether deviations are expected (based on physics) or indicate actual performance problems.

5. **Implement and validate optimisation strategies** – Operators can use the dashboard to monitor the impact of operational adjustments (e.g., pitch angle optimisation, yaw corrections, or maintenance interventions) by comparing before/after performance metrics. The dashboard tracks improvements in individual turbine KPIs and overall farm performance, providing feedback on optimisation effectiveness.

### 5.3.5 UC 5 – Regulatory Compliance and Performance Reporting

*As a compliance officer or project manager, I want to generate standardised performance reports that combine physics-based expectations with actual measured data, so that I can demonstrate regulatory compliance, validate power purchase agreement (PPA) commitments, and provide transparent documentation for stakeholders and authorities.*

1. **Configure reporting period and scope** – The user selects the reporting period (typically annual or quarterly) and specifies the scope (farm-level or turbine-level reporting). The dashboard retrieves the corresponding SCADA data and model results for the selected timeframe through the Data Processing Pipeline.
2. **Generate integrated performance metrics** – The KPI & Metrics Engine computes comprehensive performance indicators using the integrated framework, combining bottom-up (expected) and top-down (measured) results. Key metrics include AEP, capacity factor, availability, and power curve performance, all normalised and validated against industry standards.
3. **Create comparative analysis views** – The dashboard generates comparative visualisations showing measured performance (SCADA) against physics-based predictions (bottom-up) and data-driven estimates (top-down). Bar charts display annual AEP and capacity factor trends, while time-series charts show power output comparisons, providing transparent evidence of performance validation.
4. **Document performance deviations and explanations** – The dashboard highlights any significant deviations between expected and measured performance, with the integrated framework providing context for whether differences are within acceptable ranges or indicate issues requiring attention. Operators can add annotations explaining deviations (e.g., maintenance events, curtailment periods, environmental factors).
5. **Export compliance reports and data** – The dashboard generates standardised reports in exportable formats (e.g., .csv, .pdf...) containing historical KPI trends, model validation results, performance summaries, and comparative analyses. These reports combine the integrated framework outputs with measured SCADA data, providing a complete audit trail that demonstrates compliance with regulatory requirements, PPA commitments, and industry performance standards. Reports can be customised to include specific metrics required by different regulatory bodies or stakeholders.



## 5.4 Validation Strategy

The validation of the integrated bottom-up and top-down DT framework is performed at multiple levels to ensure a robust and complete implementation. Due to data confidentiality constraints, detailed numerical results from these validation activities cannot be reproduced in this public deliverable, and remain as internal project documentation. Instead, Sections 5.4.1-5.4.3 summarise the results of the validation efforts and the implications for the further development of the TWINVEST DT.

### 5.4.1 Bottom-up model (D4.1)

The bottom-up model, implemented by US in MATLAB/Simulink, was validated by Northel using data and parameters from their industrial partner MilRes' Poyra P78 wind turbine. In the validation effort, Northel re-parameterised the turbine model (including maximum power point tracking (MPPT) and power coefficient curves) to match the P78 turbine and ran a series of simulations covering the main scenarios and operating regions – start-up after cut-in wind speed is reached, variable-speed (partial-load) operation, rated operation with pitch control, and shut-down at the cut-out wind speed.

The resulting time series for wind speed against rotor speed, pitch angle and power output were checked for physical plausibility and consistency with the expected turbine behaviour. The validation confirmed that the model correctly reproduces the main operational regimes of the turbine and yields realistic trajectories, while also highlighting possible areas of improvement for the controller tuning in some unstable operational regions. The importance of proper calibration of the validated model version's power coefficient tables and parameters was also brought to attention.

Overall, Northel concluded that the bottom-up modelling methodology is sound and technically valid for use as a physics-based baseline within the TWINVEST DT, provided that turbine-specific calibration is carried out when applying it to other machines.

### 5.4.2 Top-down model (D4.2)

The top-down model methodology, developed by NTNU, has been validated on operational wind farm SCADA data from an industrial partner, with the validation procedure independently verified by Northel. The top-down framework implementation read five years of operational data, and showcased code implementations of the five module architecture (Data Processing Pipeline, KPI & Metrics Engine, Performance Baseline Models, Benchmarking and Anomaly Detection and User Interface and Integration as per Section 3.4).

This provided the user with benchmarked and contextualised KPIs such as wind power production, AEP and CF, found to be consistent with industry expectations for this type of an onshore wind farm site. CF, used as a physics-based performance baseline, is very simple and does not sufficiently account for the operating environment of the wind turbines to provide more meaningful comparisons of expected and



measured wind farm performance, a gap to be filled with higher fidelity bottom-up models. Northel reproduced the calculations from the same SCADA datasets, verified the NTNU code and confirmed the validity of the framework methodology defined in D4.2.

### 5.4.3 Integrated system (D4.4)

The integrated bottom-up and top-down framework presented in this deliverable has been implemented as a proof-of-concept dashboard by US and applied to an anonymised industrial onshore wind farm dataset (the same as in D4.2 validation). Detailed prototype description can be found in the following Section 6.

The dataset was used to drive both the top-down KPI computation and the bottom-up baseline simulations, ensuring a consistent basis for comparison. Internal verification has focused on checking data flows, KPI consistency and the behaviour of the orchestration between measured, simulated and integrated branches, using both visual overlays and quantitative regression metrics between model outputs and SCADA data. These tests show that the integrated model yields improved predictive accuracy over the stand-alone branches while preserving the KPI-oriented view required by stakeholders.



## 6 INTEGRATED FRAMEWORK PROTOTYPE

This section presents a proof-of-concept prototype demonstration of the integrated bottom-up and top-down framework in Section 6.1, followed by a discussion of the limitations of this current prototype and future work in Section 6.2.

### 6.1 Proof-of-concept Prototype

For the integrated validation, the TWINVEST framework has been applied to an anonymised onshore wind farm operated by an industrial project partner. In this case study, several years of historical SCADA and event data were provided by the partner and subsequently anonymised and normalised in accordance with the data-governance principles outlined in this deliverable. The same anonymised SCADA dataset is used consistently to validate the top-down (data-driven), bottom-up (physics-based) and integrated models, ensuring that all three approaches are assessed on an identical operational basis.

The case study wind farm is accessed via the prototype TWINVEST dashboard, which exposes both farm-wide and turbine-level views. A dropdown menu cards at the top of the interface allows the user to select either the Whole Farm or an individual turbine, illustrated in Figure 4. Depending on the selection, the dashboard retrieves and aggregates the relevant SCADA data and model outputs: farm-level KPIs when the whole-farm card is active, and turbine-specific KPIs when a single turbine is selected. Within each view, the user can switch between the top-down, bottom-up and integrated models, so that measured performance, physics-based baseline predictions and their integrated combination can be inspected side by side for the same asset and time period.

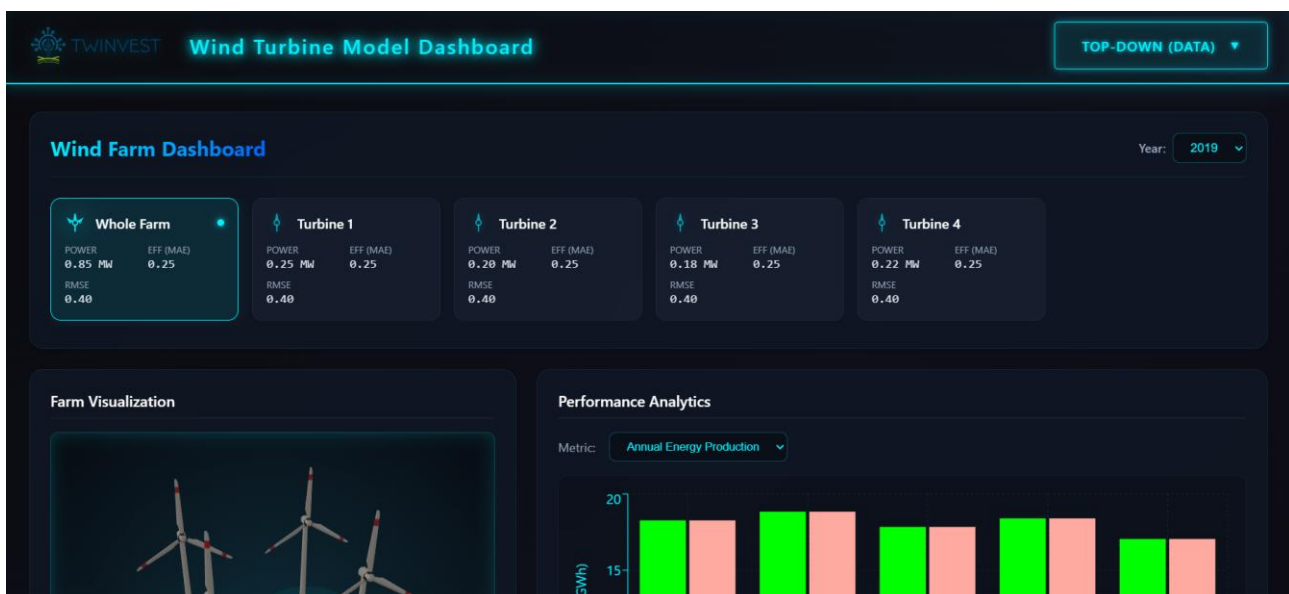


Figure 4: Proof-of-concept dashboard top-down view, showing wind farm or individual wind turbine selection, along with a drop-down performance analytics metric menu.



To support intuitive interpretation of the results, the dashboard offers multiple temporal resolutions, with options for yearly, monthly, weekly, daily and hourly analysis. For the selected horizon, performance plots are generated for both farm-level and turbine-level views. The main KPIs used elsewhere in the project are exposed directly in the dashboard, including:

- Annual Energy Production (AEP)
- Capacity Factor (CF)
- Active Power Output
- Pitch Angle
- Rotor Speed

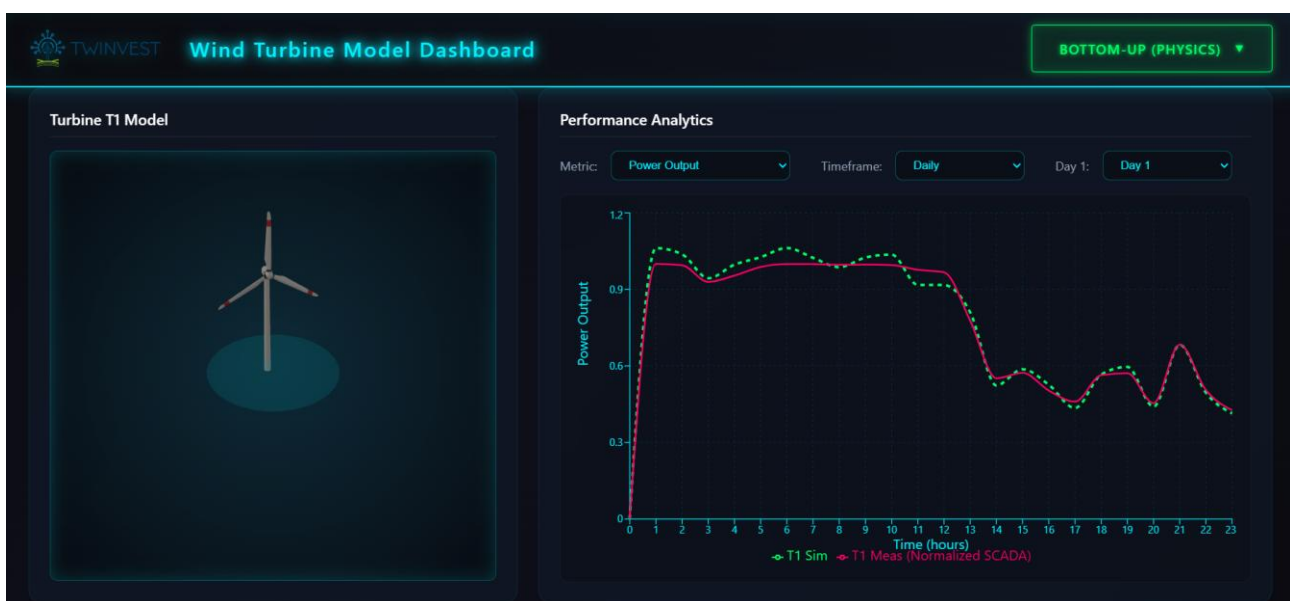


Figure 5: Proof-of-concept dashboard bottom-up view.

Additional derived quantities (such as filtered or normalised variants of the above) can be added as required. The same KPI definitions are used for both measured SCADA signals (top-down branch) and model outputs (bottom-up and integrated branches), enabling a consistent comparison across all three modelling approaches.

Visual validation is performed through a set of dashboard views that overlay measured and modelled quantities. In the *Performance Analytics* panel, time-series and aggregated plots show the evolution of AEP, CF, power, pitch angle and rotor speed over the selected timeframe, with separate traces for top-down, bottom-up and integrated results as shown in Figure 6. Farm-wide plots reveal overall production and efficiency trends, while turbine-level plots highlight machine-specific deviations or anomalies. These views are complemented by a 3D farm visualisation, which displays four turbines when the farm-wide card is selected and automatically focuses on a single turbine when an individual machine is



chosen. The 3D model provides a spatial, intuitive context for the KPI and time-series information displayed elsewhere in the dashboard.

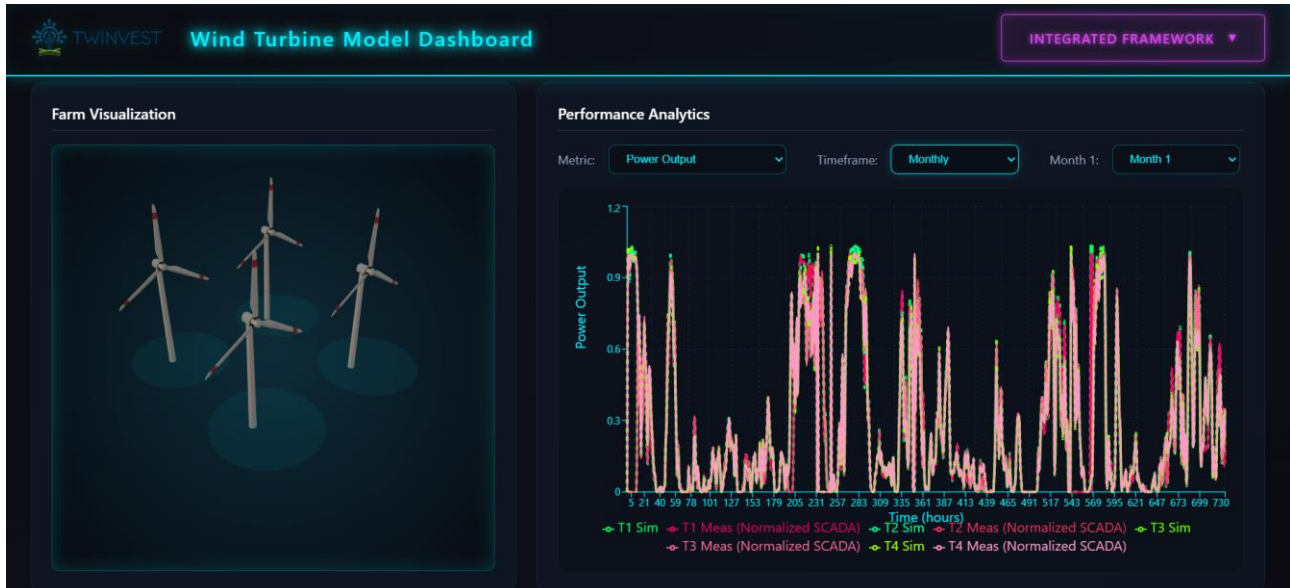


Figure 6: Proof-of-concept dashboard integrated view, including the 3D farm visualisation and both measured (top-down) and simulated (bottom-up) values for the turbine power outputs.

Quantitative assessment of the integrated framework is carried out by computing standard regression metrics between model predictions and anonymised SCADA measurements of the industrial partner’s wind farm case study. In particular, the RMSE and  $R^2$  are evaluated for key quantities such as active power and AEP-related aggregates at both farm and turbine levels. Across the analysed periods and temporal resolutions, the integrated model consistently achieves lower RMSE and higher  $R^2$  than either the stand-alone top-down or bottom-up models. This demonstrates that combining the data-driven and physics-based representations into a single integrated model yields a measurable improvement in predictive accuracy, while preserving the interpretability and KPI-oriented view required by TWINVEST stakeholders.

## 6.2 Discussion

The implementation presented in this deliverable is a proof-of-concept prototype that demonstrates the feasibility of the integrated bottom-up and top-down framework on a representative industrial case. As such, it has several limitations that should be kept in mind when interpreting the results and planning future work:

- Single wind farm and turbine type.
  - The current prototype is demonstrated on a single onshore wind farm and a single turbine type. The bottom-up model has had its parameters tuned to this configuration, having to infer some of the parameter values as those are known only to the wind



turbine's OEM. Northel's validation (see Section 5.4.1) has successfully validated the model by reconfiguring it to a different wind turbine, proving the model's generalisability, yet highlights the need of the model's requirement for additional calibration and configuration work to extend to other cases.

- Historical, offline operation only.
  - The prototype operates on historical SCADA and related data loaded from files provided by the industrial project partners. Real-time data ingestion, streaming KPI computation and live dashboard updates are not implemented yet. The implementation of such an infrastructure is recognised to be a software engineering task to be performed in later work packages.
- Limited architectural practice implementation
  - At the time of writing of this deliverable, the models and the code for the proof-of-concept showcased in this document have not been fully converted in accordance with the FMI specifications. While not a written requirement of this work package, the authors intend to perform this conversion to help their colleagues within the project facilitate the WP7 *Digital Twin Platform Integration and Testing*, and further assist with ensuring and assessing the framework's proper functionality within the full TWINVEST DT.
- Data sensitivity constraints on validation
  - Due to the confidentiality of industrial data, only anonymised, aggregated and normalised validation results can be reported in this public deliverable. More detailed numerical validation has been and will be conducted internally with project partners, but is out of scope for D4.4 in terms of published results. Some of the prototype's functionality cannot be showcased in this deliverable due to the difficulties with ensuring full anonymisation of the data.

These limitations do not affect the main conclusion of this deliverable, which is that the integration of the bottom-up and top-down frameworks is technically feasible and can be implemented in a modular way that fits the TWINVEST DT architecture. They do, however, indicate clear direction for future work packages, where broader deployment, real-time capabilities and additional models will be addressed.

Given the current data constraints, the integrated validation in its present form demonstrates the successful design and implementation of the DT system framework, building on previous work carried out within the TWINVEST project (see Section 2.3.)



## 7 CONCLUSION

This deliverable has defined and demonstrated an integrated bottom-up and top-down framework for the TWINVEST DT, developed within WP4. Building on the bottom-up framework of D4.1 and the top-down approach of D4.2, D4.4 specifies how these physics-based models and operational, KPI-driven analytics can be combined into a coherent framework that supports the main stakeholder needs identified in D1.1 and D1.2. Rather than introducing a separate system, the integrated framework is designed to fit within the layered TWINVEST architecture of D2.1, clarifying how data, models and user interfaces interact in the DT.

At the conceptual level, the deliverable formulates integration objectives and design principles that reflect both systems engineering practice and the practical constraints of industrial deployment. Key principles include modularity and loose coupling, separation of concerns and layering, interoperability and openness, explicit treatment of data governance and sensitivity, and extensibility of models and KPIs. Within this structure, the bottom-up models from D4.1 act as performance baseline engines, while the top—down components from D4.2 provide harmonised KPI computation, benchmarking and anomaly detection. The integration is realised through a set of coordinated services and FMUs in the model and analytics layer of the DT, exposed to stakeholders through dashboards and APIs in the application and UI layer.

At the implementation level, D4.4 presents a proof-of-concept prototype applied to an anonymised industrial onshore wind farm. A dashboard developed by US allows users to view farm- and turbine-level KPIs, switch between top-down (measured) and bottom-up (simulated) branches, and inspect their integrated combination across multiple temporal resolutions. Visual overlays of measured and modelled quantities are complemented by a quantitative assessment using standard regression metrics (RMSE,  $R^2$ ) between anonymised SCADA data and model outputs. Across the examined horizons and indicators, the integrated model consistently improves predictive performance relative to stand-alone top-down or bottom-up models, while maintaining a KPI-oriented view that is accessible to investors, operators and technical experts.

Validation has been carried out at three levels. The bottom-up models have been validated by Northel as part of D4.1 using their industrial partner wind turbine data. The top-down framework proposed in D4.2 has been validated on operational data from an industrial partner, and this validation effort was also verified by Northel, demonstrating that the KPI and benchmarking logic behaves as expected and can support wind farm performance assessment. Finally, the integrated system has been validated through the D4.4 dashboard prototype using the anonymised industrial case study.

The prototype and its validation also highlight current limitations. The implementation is demonstrated on a single onshore wind farm and turbine type, operates on historical data only, and exposes only a subset of the KPIs and models planned for the full TWINVEST DT. Due to data confidentiality constraints, detailed validation results cannot be reported in this public deliverable, and some prototype capabilities cannot be fully showcased, but its limitations and future work are discussed.



Despite these constraints, D4.4 shows that a modular integration of bottom-up and top-down approaches is technically feasible and aligned well with the overall TWINVEST system architecture. The resulting framework defines natural entry points for specialised models developed elsewhere in the project, and a structure within which they can be expressed in a common KPI language and exposed through a unified interface. Future work in proceeding work packages will build on this foundation by extending the set of models and KPIs, increasing the level of automation and configurability, and progressing towards enabling real-time deployment on multiple wind farms. In this way, the integrated framework developed in D4.4 forms a key step towards a practical onshore wind farm-focused DT that supports both operational decision-making and long-term investment analysis.



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