

Reply to reviewers' comments for the preprint "Adaptive economic wind turbine control"

(<https://doi.org/10.5194/wes-2025-101>)

The authors would like to thank the two reviewers for their time and for the useful feedback. All the inputs that they provided have contributed to the improvement of the paper.

A list of point-by-point replies to the reviewers' comments is reported in the following. The reviewer's comments are in black, and our replies in blue.

We have taken the opportunity of this deep revision to improve readability and understanding by rephrasing and expanding the text in multiple places, by including new explanations and adding bibliographical references.

A revised version of the manuscript is attached to the present reply, with additions highlighted in blue and corrections/deletions marked in red.

The authors

Reviewer 1

(<https://doi.org/10.5194/wes-2025-101-RC1>)

Summary

The paper investigates the use of an adaptive economic nonlinear MPC, known as ENMPC for wind turbines. The aim is to optimize turbine profit by optimising power generation while reducing fatigue damage cost. The profit-based approach is interesting to those of us who have worked on control methods to reduce turbine fatigue loads. Typically, control performance is measured by reducing DELS. The current paper seeks to take this further by replacing DELS with measurements of tower damage costs, extending earlier work by this group of authors on economic MPC. The novelty of the current contribution is enhance the ROM dynamics used for the MPC control scheme by adding a corrective term to compensate for the mismatch between the ROM and the actual wind behaviour. Studies show a 9% increase in the cumulative profit relative to an economic MPC scheme that did not include the adaptive model correction term. As such the paper contains sufficient novelty and worthwhile results to be potentially publishable.

Comments

Nonetheless there are significant limitations and issues with the proposed method that need to be further addressed.

1. Given the power generation term in (17), how does MPC avoid exceeding rated power in Region 3? The simulation scenario shown in Figure 6 is for a 11 m/s wind speed which is in Region 2 for the 5 MW turbine.

The proposed ENMPC optimization formulation avoids exceeding the power limits (as well as limits on other system states) due to the bound constraints, shown in Eq. 14(c), on the set x_c .

Equation (16) shows the composition of the set x_c , where the last element ($\eta_{gen}\omega T_g$) denotes the electrical power generation (P_{gen}). This ensures that both the direct and derived system states remain within the desired bounds throughout the operational range of the turbine.

To make this more explicit, Eq. (16) has been modified to explicitly show P_{gen} in the set.

2. The proposed method is conceptually complicated, and requires considerable computational resources to train the NN. In the given study, the FAST turbine simulator was used. There needs to be some discussion of the feasibility of training the NN on a physical turbine.

Thank you for your comment, which allowed us to more clearly make the point that our proposed method is not computationally demanding.

The proposed data-driven model adaptation utilizes an offline-trained NN to implement the corrective term, in contrast to an online adaptation, which allows real-time adjustment (please refer to lines 63-70 of the manuscript for details). For our proposed offline model improvement, the more computationally demanding aspect is the generation of a dataset that encompasses the range of operating conditions of the turbine, and that is used to train the NN. Once the dataset has been obtained, the training process of the NN is computationally trivial.

The IEC 61400-1 Standard requires wind turbine OEMs to conduct turbine simulations under different conditions for certification and testing purposes. The OEMs typically have validated high-fidelity turbine models from the design and prototyping phases. According to the specifications in the IEC standard, for design load cases (DLC) 1.2 denoting normal operation of the turbine, the total number of data points is 3,312,000, assuming 6 turbulence seeds and a sampling rate of 0.1 seconds. The NN used in this work was trained using only 216,071 data points, showing that OEMs may already have access to the basic dataset required for the usage of the proposed methodology.

With reference to Fig. 5, the results indicate that the relative improvement due to the proposed correction begins to plateau, starting with models trained using only 85% of the training dataset, which corresponds to 183,660 data points. This

further supports the argument that OEMs can apply the proposed approach for improved closed-loop performance with minimal extra simulation costs.

We have expanded the discussions in sections 2.2, 4.1.2 and 5 to clarify the computational effort, including the comparison with the number of data points that one routinely generates in standard design and certification activities.

3. Its not clear if the adaptive MPC controller could be implemented sufficiently rapidly for real time implementation, even with the computational resources available for simulation.

Thank you for the remark. In comparison to existing (non-adaptive) economic MPC, the proposed approach adds an offline-trained NN, which is only queried during online closed-loop control. Querying a NN typically implies only a very small computational burden, which is certainly smaller than the time required for the solution of the underlying optimization problem. Hence, we believe that the proposed model adaptation will be real-time feasible if the original MPC implementation is real-time feasible.

However, as mentioned in a few places throughout the document, the optimization of the computational performance of the controller for real-time feasibility was not the focus of this work. The goal here is to show that a fatigue-aware adaptive economic MPC (which did not exist) is possible, delivers superior performance, and does not require an unrealistic computational effort and an exceedingly large training dataset. Based on this result, future work can look into the optimization of the software for field deployment, which is however a different narrow-focus activity that depends to a significant extent on the specific hardware and software platforms that are chosen.

4. A comparative study of profit generation should provided against a well-designed baseline controller, such as ROSCO (see Abbas et al, A reference open-source controller for fixed and floating offshore wind turbines, Wind Energy Science, 2022) to see if the extra computational efforts yield some meaningful performance improvement. The widely used NREL baseline controller of Wright and Fingersh, Tech. Rep. NREL/TP500-42437, 2008 should preferably be avoided as it has been convincingly superseded by ROSCO.

Thank you for the comment. We understand the relevance of comparing the performance of an economic MPC to a well-designed baseline controller, e.g. ROSCO [Abbas2022] and PID [Jonkman2009] controllers, to quantify the trade-off between economic gains and controller complexity. However, there is existing literature on WTC using economic MPC that offers performance comparison against baseline controllers and standard MPC controllers. For the WT revenue maximization objective, [Pustina2022, Hovgaard2014, Yan2013] compares an economic MPC formulation to baseline controllers, whereas [Gros2013,

Gros2017] compares economic MPC with standard MPC formulation, demonstrating that the ENMPC formulation results in better performance over baseline controllers. For the WT profit (difference of revenue and fatigue cost) maximization objective, [*Loew2020b, Loew2022, Soleymani2024, Wang2025*] show that the economic MPC formulation performs better than the baseline PID controller.

These studies already demonstrate that the economic MPC outperforms the baseline controllers. As the scope of our study is to implement PORFC in an adaptive ENMPC formulation and evaluate the benefits of such an adaptive ENMPC, we focus on comparing augmented and non-augmented economic MPC formulations to quantify the performance improvement resulting from model adaptation.

Please also note that standard PID-based controllers: are unable to explicitly optimize an economic figure of merit; cannot take fatigue damage into account using the exact rainflow counting algorithm used in PORFC; are not based on physical models, and therefore cannot be truly adapted to improve their performance as done here, as only their gains can be changed/scheduled; cannot use preview control as an MPC does. All these effects limit the performance of standard controllers when compared to MPC, as already extensively reported by previous studies.

We have taken this opportunity to expand the introduction and results sections to highlight this point.

5. Another significant limitation is that in an operational setting, profit will depend upon the prevailing power prices, but the authors have assumed a constant power to revenue factor, equivalent to assuming constant power prices. The simulation results would be a lot more convincing if real-world power prices were employed in the case study.

Thanks for the remark, in fact this point was unclear in our original manuscript.

The fact that the proposed methodology uses an MPC framework implies that any kind of short-term variability in the external variables (such as ambient conditions, market prices, etc.) can be directly included within this time-series-based online optimization.

In any case, even in a scenario where the turbine is part of a bigger cluster that is participating in energy markets, the most dynamic variations are around 15-minute intervals coming from intra-day markets. This is much longer than the duration of a typical ENMPC horizon employed for WTC. Intra-quarter-hourly variations are only possible for balancing markets, however, the participating entities are remunerated based on the offered capacity and provided energy separately.

We have now expanded section 3.1, explaining that -although the energy price appears outside of the integral in Eq. (17)- this does not mean that energy prices cannot change. The formulation is fully applicable to variable electricity prices, but this variability -since it takes place at much slower time scales- does not need to enter the MPC problem that is solved at each time step. The applicability to time-variable prices has been now noted also in the conclusions section.

In some places found the paper hard to read, the following comments relate to improving clarity:

6. Page 5: V_w is introduced in line 122 but not defined until Line 135. There is no discussion of how wind speed is to be interpreted, is REWS intended?

V_w is introduced and defined in the second sentence (Line 109 of the original manuscript) of Sect. 2.1: “The incident wind V_w induces an aerodynamic torque T_Q about the rotor axis and an aerodynamic force F_T along it.”

In the context of the reduced order model (ROM) formulation, V_w represents the disturbance input to the model. Using rotor effective wind speed (REWS) for closed-loop evaluation (as considered in the proposed formulation) is one possible way to interpret this. However, one could also use measured wind speed at a certain point on the nacelle (obtained by filtering anemometer measurements) as an input to the ROM. An alternative possibility includes using rotor-averaged wind speed (RAWS) to compute V_w . These scenarios are explicitly discussed in this work in Sect. 4.3.2.

For the sake of generality and the discussions offered in this work, we believe that the definition of V_w , as presented in Sect. 2.1 is sufficient.

7. In line 122, It is also interesting that the authors include the adjusted wind speed $V_w - \dot{(d)}_{T_{FA}}$ in their aerodynamic torque and force component terms; given that wind speeds will be above 8 m/s in typical operating conditions, is the tower bending velocity $\dot{(d)}_{T_{FA}}$ generally large enough to warrant inclusion?

Yes. The methodology is generic and not tailored to a specific wind condition or wind turbine design. While the effect of the tower motion might be small in some cases, it might be significant in others. Hence, the inclusion of the tower bending velocity (given that it is already available as a system state) in the ROM formulation was considered as a valuable addition, especially because it is easily included in this model-based formulation and comes at essentially no extra computational cost or complexity.

8. In (9), why is V_w given in brackets?

Thank you for your observation. Brackets are used to denote a set of variables. As the set of disturbance inputs shown in Eq. (9) contains only one variable V_w , the use of brackets is unnecessary in this case. Thus, we have removed them.

9. In (12) its not really clear how the inputs and outputs of the NN in (10) relate to the wind turbine model. What is an activation function?

The formulation in Eq. (10) (now Eq. 11 in the revised manuscript) is presented in a generic form, showing the analytical mapping of NN outputs and inputs in a NN. Eq. (12) (now Eq. 13) only shows the parameters of the neural network (NN), so the weights and biases.

This allows the user to apply the proposed methodology to a system that can be represented using a ROM, without loss of generality. The application of the methodology to wind turbines has been discussed extensively in Sect. 4.1.

In the context of NNs, an activation function is a nonlinear mathematical mapping applied to the weighted sum of a neuron's inputs (plus bias) to produce its output. It determines whether and to what extent a neuron is activated, thereby enabling the network to model complex, nonlinear relationships between inputs and outputs.

Although this is textbook material, we have included the definition of the activation function in Sect. 2.2 of the revised manuscript, for better clarity.

10. Line 165: 'data is obtained using a high-fidelity simulation model' but there is no discussion of which high-fidelity simulation model is used. Also, the wind profiles and control inputs to compute the states of both the ROM and hi-fidelity model have not been discussed. Are the NN parameters p in (12) independent of the wind profile used?

The methodologies discussed in Sect. 2 and Sect. 3 are deliberately kept non-specific, for the sake of generality and to avoid loss of applicability. The proposed methodology is then applied to wind turbines, and the application-specific details are extensively discussed in Sect. 4.1. Hence, the details regarding the simulation model, data generation, pre-processing, and NN training are presented only in Sect. 4.1.

Yes, the NN parameters are trained using full-field turbulent wind profiles, representative of real turbine inflow conditions. The dataset used for training should span all operating conditions (including wind profiles) where the NN will later be used.

11. In (14a) the functions $J^{\{FA\}}$ and $J^{\{SS\}}$ are not defined until (18a)-(18c), which makes this section hard to read.

Thank you for this useful comment. Indeed, the optimization problem is rather complex and depends on various variables and terms. We have now added a sentence just below Eq. (18) to explain that the various terms are sequentially explained one by one in the following subsections.

12. Also the constraints (14c) to (14f) need more justification, since these quantities are all vectors, how can they satisfy an inequality?

We believe this is standard notation for constraints. The meaning of the notation is that each of the elements of a vector is subjected to its own constraint, i.e. the constraint is applied individually to each scalar component.

For example, Eq. (14e) shows the bound constraint on ξ . As the set ξ contains two elements ξ_1 and ξ_2 , Eq.(14e) denotes that each of these elements is constrained to its respective upper and lower bounds.

13. Line 208: the statement ‘aims to maximize the generated profit by balancing the revenue accrued from wind power generation and cost incurred due to fatigue damage’ seems a little strange, since if the revenue and costs are balanced, the profit will be zero.,

Thanks for the remark. Clearly “balanced” does not mean that the two terms are the same and cancel out to zero. Additionally, the contrasting effects of revenue and cost are mentioned in multiple places in the introduction, in the body of the manuscript, and in the conclusions. In any case, we have modified the sentence to make the meaning clearer.

14. In line 218, referring to (17), we are told that ‘in this work the aerodynamic power is maximized.’ I understand this to mean w_P , used to covert to power to revenue, is assumed constant at all times. While the turnpike effect needs to be avoided (short term power maximization by extracting energy from the blades), such a simplifying assumption would seem to render the present study unsuitable for implementation in realistic operating scenarios where the power prices fluctuate considerably in short time intervals and are known only a short time in advance.

Thanks for the remark. Please refer to our response to comment 1.5, which already addresses this point. In short, w_P is not necessarily constant, it simply is outside of the integral because it changes much slower than the system dynamics that need to be captured by MPC within the optimization horizon. This point has now been made clearer in the revised manuscript.

15. In Line 223, the values of c have not been defined. In (18a) we see that c can equal 1 or 2, but the physical meaning remains obscure.

Thanks for the observation and the feedback. We have now defined 'c' in the same paragraph and have also included discussions regarding the physical meaning and possible values that 'c' can have within the PORFC algorithm in Sect. 3.1.

16. In (18a), it's not clear how the $J^{\{FA\}}$ function (and $J^{\{SS\}}$) yields costs in revenue units (e.g. dollars, euros) that can be compared with the revenue units used $J^{\{power\ generation\}}$ to compute profit. In particular, if t_0 is the time of commissioning a new turbine and t_{end} is 20 years, the expected life span of the turbine, is it true that $J^{\{FA\}} + J^{\{SS\}} = a_m$, the capital cost of the turbine?

Yes, that is the assumption here. This methodology of obtaining the cost of accrued damage as a proportional share of component capex is quite common in the literature and has been presented in detail here [*TotalControlD21*].

The determination of a_m from the capex, in this work, can be found in a previous publication from our group [*Loew2023*].

We have taken this opportunity to provide a table showing the values of different relevant parameters and corresponding references in the revised manuscript.

17. Line 255: Should blade pitch rate also be subject to an inequality constraint?

Thank you for the question, but we do not see any reason why pitching rate should not be subject to inequality constraints.

The blade pitch rate is determined by the actuator limits, and it is useful to inform the turbine controller of the maximum allowed pitch rate. In the absence of such a condition, the controller might be requesting a pitch rate that is not really achievable, and this would negatively impact performance.

18. In Line 288, why are β_g and T_g described as disturbance inputs? Are they not control inputs? Also, in (20) $\nu(t)$ is undefined.

β_g and T_g are indeed the control inputs for the ENMPC optimization problem shown in Eq. (14). However, for the moving horizon estimator (MHE), the ENMPC sets these values, and are external to the MHE optimization problem shown in Eq. (19). The decision variable for the MHE optimization problem is the noise variable $\bar{\nu}$.

In Eq. (20), $\nu(t)$ is a typo, and the correct quantity should have been $\bar{\nu}(t)$. Thanks for noticing the mistake. We have corrected it in the revised manuscript.

Reviewer 2

(<https://doi.org/10.5194/wes-2025-101-RC2>)

Summary

This paper proposed an adaptive economic nonlinear MPC for wind turbines, which aims at reducing plant-model mismatch, and improving control performance with adaptivity. Similar with other EMPC design, the controller maximizes profits by balancing (fatigue damage) cost with revenue of power production. Adaptivity comes from the internal gray box model which is a combined physics and data-driven correction terms trained offline. This paper also showcases the improvement in state predictions compared to the regular non-adapted baseline method. The results show that the adaptive EMPC has higher economic profit with lower pitch and torque travels, compared to the baseline one. The computational cost is discussed in this paper.

In general, this paper is well organized, technically sound and presents some original contributions in adaptive EMPC of wind turbines, mainly the integration of PORFC and combined ROM and offline-trained neural network corrections to minimize the plant-model mismatch. This paper is recommended to accept after minor revisions. Below are some specific comments that can be considered in revision:

Comments

1. Page 1-2 Introduction: The introduction is clear, but it does not sufficiently indicate the difference of this work from existing adaptive MPC studies. The authors need to explicitly state how this work (integration of PORFC with NN-offline adaptation) advances beyond prior work on adaptive MPCs.

Thank you so much for the feedback. We have added a new paragraph in the introduction section to include additional references on adaptive economic MPC for profit-maximizing wind turbine control and have tried to more clearly highlight the existing gap.

2. Page 4 equation (1): Need more clarity about the free parameter p . How is it obtained by data and how is it related to the NN's input/output?

The free parameter set \mathbf{p} in Eq.(1) denotes the parameters of the model correction term $\Delta \mathbf{F}_{ROM}$. These parameters are essentially the optimal values of the weights and biases of the neurons of different layers of the trained neural network (NN), as shown in Eq.(12) (now Eq. 13 or the revised manuscript).

The free parameter set \mathbf{p} is obtained by training the NN using the input and target data, hence, mapping the NN input through the NN architecture to obtain the respective output.

3. Page 6 equation (10): How do you choose activation function here? The author should brief explain, e.g. why a radial basis activation was chosen, and how it affects the numerical stability.

The activation function was decided here according to the following criteria:

- The prediction performance of the NN
- The activation function should be continuous and differentiable (smooth)

As the ENMPC internal model requires smooth functions for numerical stability, radial basis functions networks such as gaussian functions provide continuous differentiability allowing for calculation of gradients and Hessians.

A new sentence has been added in Sect. 2.2 to highlight the factors governing the choice of activation function.

4. Page 6 equation (11): Does it normalize across the entire dataset or per feature per batch?

The normalization is done per feature for the entire dataset, as shown in Eq. (11) (now Eq. 12 in the revised manuscript). There is no sequential training considered in this work and no normalization per batch.

5. Page 7 equation (14): The objective terms (profit, fatigue cost) are introduced without scaling discussion. How these terms are weighted or normalized? What's the rationale for chosen weights?

The objective terms (revenue, fatigue costs) of the proposed optimization are not weighted randomly but rather using their respective actual economic values. For example, the weighting term to calculate revenue due to power production is the revenue rate w_p , as shown in Eq. (17). Similarly, the cost due to accumulated tower fatigue damage is weighted using the initial capital cost parameter a_m through the online rainflow analysis, as shown in Eq. (18).

We realize that this had not been explicitly mentioned in the paper. We have now added a new paragraph in section 3.1 to make this clearer. Thank you for the useful comment.

6. Page 9 equation (18): Parameters, R_m and m are introduced and used later without references or values. Add a table summarizing all parameters, their sources used for the case study.

Thank you so much for the comment. We have now included two tables listing the parameters considered in the study.

7. page 16 Figure 5: The dataset size sensitivity analysis is interesting but lacks explanation of why performance plateaus at 85%. Discuss whether this is due to model saturation or just dataset redundancy.

Thank you for your comment. For the said analysis, the performance starts to plateau at 85%, because all possible trends are mostly captured with that amount of data. Any additional data does not bring new information to the model. This has now been explicitly noted in the paper.

8. Page 22 Figure 22: It is great to see the computational feasibility, but the absolute CPU times per control iteration are missing.

We are not in favor of reporting absolute CPU times. As real-time feasibility and computational performance optimization of the ENMPC has not been the focus of this work, we believe that it is more interesting to look at the relative impacts.

Furthermore, the absolute numbers will become less relevant in future with the use of high-performance computing platforms and additional software optimization (not considered here). Additionally, absolute CPU times very rapidly become obsolete, therefore adding very little value to the discussion.

9. Page 24 Conclusion: while future research direction is briefly mentioned, this paper can give a more explicit discussion on potential extension, e.g. extending PORFC to other fatigue-critical components of wind turbines.

Thank you for the comment. We have expanded the 'future work' section of the revised paper, highlighting further the usage of PORFC in other fatigue-critical components.

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Adaptive economic wind turbine control

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Abstract.

Model predictive control (MPC) for wind turbines offers several interesting advantages over simpler techniques, as for example the direct optimization of a goal function, the inclusion of constraints, non-linear coupled dynamics, and wind preview (when available). To enable real-time execution, MPC uses a reduced order model (ROM) that approximates the dynamics of the controlled system using only a limited number of degrees of freedom. As a result, the accuracy of the ROM is often the main limit to the performance of MPC. To address this problem, an adaptive controller-internal model can reduce plant-model mismatches, potentially leading to improved performance.

This work proposes an adaptive economic nonlinear MPC (ENMPC) for wind turbines. The controller maximizes profit by optimally balancing fatigue damage cost with revenue due to power generation. The cyclic fatigue cost is formulated directly within the controller using the novel parametric online rainflow counting (PORFC) approach. PORFC provides a rigorous continuous expression of the discontinuous cyclic fatigue cost using time-varying parameters. Adaptivity is obtained by a controller-internal grey-box model that combines reduced order physical dynamics with data-driven correction terms. These are implemented via a neural network that is trained offline. Additionally, system state and disturbance estimators are included in the closed-loop controller.

The improvement in state predictions due to model adaptation is first assessed and compared with respect to the non-adapted baseline ROM in open loop. The performance of the adaptive ENMPC and the impact of a reduced plant-model mismatch is then assessed in closed loop for a reference multi-MW onshore wind turbine in a realistic simulation environment. Results show that the adaptive ENMPC yields higher economic profits at significantly lower pitch and torque travels, compared to the baseline non-adaptive ENMPC. While the enhanced closed-loop performance and economic gains of the proposed model adaptation are significant, they come at the cost of a slight increase in the computational burden of the controller.

1 Introduction

1.1 [Beyond power maximization: economic wind turbine control](#)

Wind turbine operation and control have recently shifted from the traditional goal of power maximization to more economically driven goals. In this new paradigm, turbines are operated with damage awareness in mind ([Barradas-Berglind and Wisniewski, 2016](#); [Gros and Njiri and Söffker, 2016](#); [Barradas-Berglind and Wisniewski, 2016](#); [Loew and Bottasso, 2022](#); [Anand et al., 2022](#); [Loew et al., 2023](#)). This shift is driven by the impact of fatigue damage, which shortens the operational life of turbines and increases operation

and maintenance (O&M) costs. In fact, these factors are critical to the economic profitability of operators of wind energy assets (Canet et al., 2021; Stehly et al., 2020).

30 One widely used method for developing economic controllers for wind turbines is model predictive control (MPC) (Rawlings et al., 2017). MPC optimizes control actions over the short-term future by predicting system behavior, and then solving an economic optimization problem based on these predictions (Rawlings et al., 2012). ~~When~~ Existing literature shows that economic MPC formulations for wind turbine control – using the conventional objective of maximizing revenue from power generation – achieve better performance than baseline controllers and standard MPC approaches (Pustina et al., 2022; Gros and Schild, 2017; Hovgaard. However, when considering wind energy systems, an economic optimization should balance the conflicting objectives of maximizing revenue from power generation and of minimizing the cost of fatigue-related damage. Additionally, a controller should always guarantee that the system operates within feasible limits. The effectiveness of the controller ultimately depends on the quality of the solution of this constrained optimization, which essentially relies – not only on the economic model – but also on the quality of predictions of the controller-internal model.

1.2 The challenge of including fatigue in control formulations

40 The existing literature on the economic control of wind turbines using MPC is based on two main approaches for estimating cyclic fatigue: indirect and direct methods.

The indirect approach uses a proxy for fatigue (~~Barradas-Berglind and Wisniewski, 2016; Gros and Schild, 2017~~) (Barradas-Berglind and . This method is convenient because it avoids the use of cycle counting that, because of its branching nature, introduces discontinuities in the calculations (Loew et al., 2021). As a result, with the indirect approach gradient-based methods can be used to solve the optimization problem. However, this also means that fatigue is only approximatively taken into account through a proxy quantity, which might not always provide for accurate results.

The direct approach, on the other hand, estimates fatigue explicitly using online cycle counting directly within the MPC framework (Loew et al., 2020b; Anand et al., 2022). This method, termed parametric online rainflow counting (PORFC), is relatively new and was first introduced in our previous work Loew et al. (2020a). It has since been applied in its fundamental form in various contexts, including wind turbine fatigue control (Loew et al., 2020b), battery cyclic aging control (Loew et al., 2021), and control of grid-connected wind-battery hybrid systems (Anand et al., 2021, 2022). To the authors' knowledge, PORFC is the only approach that allows for the rigorous treatment of fatigue, as it was ~~design~~ designed to produce the same results on receding horizons that would be obtained by cycle counting the whole response time history a posteriori (Loew et al., 2020a).

55 1.3 The challenge of relying on controller-internal models of reduced complexity

In both approaches mentioned above, the controller relies on an internal model of the wind turbine to predict its behavior over the MPC horizon. However, due to computational effort and time constraints, the internal representation of the system response is typically obtained through a reduced order model (ROM). ROMs approximate the system dynamics using a limited number of degrees of freedom (DOFs), enabling the real-time execution of the controller. The accuracy of these predictions plays a crucial

60 role in the performance of the controller. A closer match between the predicted and actual wind turbine dynamics allows for the controller to make more precise decisions when optimizing the objective function, while at the same time ensuring compliance with system constraints. In fact, the degree of model mismatch not only affects optimality, but may also impacts the ability of the closed-loop system to operate strictly within admissible or desired limits.

One way to address model mismatches is by using state observers and estimators (Anand et al., 2022; Loew and Bottasso, 65 2022), where measurements of the response of the wind turbine from previous time steps are used to estimate and adjust the initialization of the controller for the next step. However, the effectiveness of this approach is limited when estimates are obtained from underlying models of scarce accuracy.

A more compelling alternative is to adapt the internal model dynamics of the controller, either by using measured operational data or synthetic results from models of sufficiently high fidelity that can accurately represent the plant behavior. One of the 70 aims of this paper is to develop practical methods for enabling adaptivity in wind turbine ROMs.

1.4 Offline adaptation for certifiable learning control

Data-driven adaptation can be implemented online, offline, or in a hybrid manner, each of these options offering distinct trade-offs in terms of advantages, challenges, and practical applicability to economic control.

Online adaptation allows for quickly adjusting model behavior in real time based on observed plant response. However, for 75 industrial applications, it is difficult to imagine how one could guarantee the correct learning of model corrections, and how such a system could be demonstrated to be always safe and certifiable in practice.

In contrast, offline adaptation allows for the systematic integration of data, enabling a rigorous verification and validation of any learned correction terms prior to their deployment in the field. A rigorous offline verification and validation opens the door to the certification of adaptive controllers, which must meet strict standards in terms of performance, safety, and reliability 80 before deployment in real-world operations.

In the context of economic MPC, offline model adaptation can be achieved in several ways: by adjusting the parameters of the ROM (Schreiber et al., 2020), or by incorporating a correction term into the ROM or MPC optimization function (Bottasso et al., 2006; Collet et al., 2021; Soloperto et al., 2022), or by a combination of both methods. ~~Since-~~

It is however important to note that a ROM captures only ~~some-selected~~ aspects of the behavior of the plant ~~,-the-sole~~ 85 ~~tuning-of-its-parameters-~~ and does so only with limited accuracy. As a consequence, tuning of ROM parameters alone is often insufficient and ~~might-actually-lead-to-nonphysical-values-of-the-parameters~~ may even produce non-physical results, because parameter tuning cannot compensate for missing physics. Instead, data can be leveraged to learn and incorporate the missing physics into the internal model ~~of-used-by~~ the controller. This is ~~indeed~~ the approach followed herein this work.

The few existing studies on adaptive economic MPC for wind turbine control focus primarily on the tuning of controller 90 gains (Shaltout et al., 2018; Tang et al., 2023). These works rely on simplified linearized models and Bayesian optimization techniques to achieve robust performance under uncertain and varying wind conditions, but they do not explicitly address model mismatch. More in general, gain tuning cannot compensate for missing or inaccurate representation of relevant physics. Recent

contributions to economic MPC introduce more complex, nonlinear internal models (Pustina et al., 2022, 2025); however, these approaches still lack adaptive mechanisms that explicitly compensate for modeling errors.

95 Furthermore, although the economic optimization in all of these studies incorporates profit-related objectives, it relies solely on indirect penalization of system states and does not explicitly account for fatigue damage, whose relevance has been highlighted by Loew and Bottasso (2022) and Anand et al. (2022).

1.5 Towards model-adaptive fatigue-aware economic wind turbine control

The key contribution of this work is the development of a novel fatigue-aware economic nonlinear model predictive controller
100 (ENMPC) with offline-adaptive capabilities enabled by data-learned ROM corrections.

The controller maximizes profit by balancing two competing factors: revenue from power generation and costs associated with fatigue damage of the turbine components. The cost of cyclic damage is formulated using the novel PORFC approach, which performs online rainflow analysis over the stress history and its future predictions to generate time-varying parameters. These parameters are then used to obtain a continuous expression of the discontinuous fatigue cost, which is incorporated into the MPC optimization. The ~~controller-internal model is a grey-box that combines reduced-order physical dynamics with offline-computed correction terms. These terms are formulated as neural networks trained on high-resolution measured or synthetic data of the wind turbine. Their objective is to reduce model mismatch, thereby improving online closed-loop performance.~~ profit formulation used here does not explicitly incorporate the effects of fatigue on component reliability and O&M costs, simply because of a lack of data and appropriate models linking loads with failure rates, instead representing
105 ~~fatigue-related costs solely through the amortization of the overall component cost, as discussed in TotalControl (2022).~~

The controller-internal model is a grey-box that combines reduced order physical dynamics with offline-computed correction terms. These terms are formulated as neural networks trained on high-resolution measured or synthetic data of the wind turbine. Their objective is to reduce model mismatch, thereby improving online closed-loop performance.

The paper is structured as follows. Section 2 introduces the proposed model adaptation approach. It describes both the
115 simplified wind turbine model used as internal ROM, and the data-driven modeling of the correction term. Section 3 provides a detailed formulation of the ENMPC, discussing various aspects of the underlying optimization problem. This section also describes the state and wind speed estimators, which provide initial conditions and disturbance predictions for the ENMPC. Section 4 presents and discusses the results from a case study. The analysis begins with an open-loop assessment of the model adaptation approach, followed by a closed-loop evaluation of its impact on economic performance, actuator usage, and
120 computational burden. Additionally, this section examines the benefits of the proposed model adaptation under different wind input and preview scenarios. Section 5 summarizes the key findings of this work and outlines potential directions for future research.

2 Model adaptation

The proposed model adaptation approach enhances the ROM dynamics by introducing a data-driven correction function, $\Delta \mathbf{F}_{\text{ROM}}(\cdot)$. This function is designed to compensate for the mismatch between the ROM and the actual wind turbine behavior. The adapted model dynamics, denoted as $\mathbf{F}_{\text{ROMaug}}(\cdot)$, can be expressed as

$$\dot{\mathbf{x}}(t) = \mathbf{F}_{\text{ROM}}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t)) + \Delta \mathbf{F}_{\text{ROM}}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{d}(t), \mathbf{p}), \quad (1)$$

where $\mathbf{F}_{\text{ROM}}(\cdot)$ represents the original nonlinear ROM dynamics. By ~~incorporating~~ adding the corrective function $\Delta \mathbf{F}_{\text{ROM}}(\cdot)$, the adapted model more accurately captures the behavior of the plant. Here, $\mathbf{x}(t)$, $\mathbf{u}(t)$, and $\mathbf{d}(t)$ represent the continuous system states, control variables, and external disturbances, respectively. The correction $\Delta \mathbf{F}_{\text{ROM}}$ depends on these same quantities, but also on free parameters \mathbf{p} that are learnt based on data.

2.1 Reduced order model

A simplified wind turbine model with only three degrees of freedom (drivetrain angular speed, and tower fore-aft and side-side deflections) is considered to represent the ROM dynamics $\mathbf{F}_{\text{ROM}}(\cdot)$. The incident wind V_w induces an aerodynamic torque T_Q about the rotor axis and an aerodynamic force F_T along it. The aerodynamic torque directly excites the drivetrain rotational dynamics

$$J_r \dot{\omega} = T_Q Q_a - T_g Q_g, \quad (2)$$

ignoring mechanical losses, where J_r , ω , and $T_g Q_g$ represent the rotor moment of inertia, rotor speed, and generator torque referred to the low-speed shaft, respectively. The aerodynamic force F_T , coupled with the drive-train dynamics, excites oscillations in the tower. These can be quantified by using the tower-top ~~deflection~~ deflections in the fore-aft ~~direction~~ (noted $d_{T_{\text{FA}}}$, ~~having dynamics~~

$$\underline{\underline{\ddot{d}_{T_{\text{FA}}} = \frac{1}{f_1} (F_{T_{\text{FA}}} - f_2 \dot{d}_{T_{\text{FA}}} - f_3 d_{T_{\text{FA}}})}},$$

~~and the tower-top deflection in the~~) and side-side ~~direction~~ (noted $d_{T_{\text{SS}}}$, ~~having dynamics~~

$$\underline{\underline{\ddot{d}_{T_{\text{SS}}} = \frac{1}{s_1} (F_{T_{\text{SS}}} - s_2 \dot{d}_{T_{\text{SS}}} - s_3 d_{T_{\text{SS}}} - s_4 T_g)}}.$$

) directions, which are governed by the following equations of dynamic equilibrium:

$$\underline{\underline{\ddot{d}_{T_{\text{FA}}} = \frac{1}{f_1} (F_{T_{\text{FA}}} - f_2 \dot{d}_{T_{\text{FA}}} - f_3 d_{T_{\text{FA}}})}}, \quad (3a)$$

$$\underline{\underline{\ddot{d}_{T_{\text{SS}}} = \frac{1}{s_1} (F_{T_{\text{SS}}} - s_2 \dot{d}_{T_{\text{SS}}} - s_3 d_{T_{\text{SS}}} - s_4 Q_g)}}. \quad (3b)$$

These Tower oscillations result in cyclic stresses $\sigma_{FA}(t)$ and $\sigma_{SS}(t)$, respectively, at tower base. Here, $F_{T_{FA}}$ and $F_{T_{SS}}$ represent the rotor-orthogonal-rotor-plane-orthogonal (thrust) and rotor-in-plane-rotor-in-plane (side-side force) components of the aerodynamic force F_T , whereas f_{1-3} and s_{1-4} are model parameters. The aerodynamic torque $T_Q(\omega, \beta_b, (V_w - \dot{d}_{T_{FA}}))$ and force components $F_{T_{FA}}(\omega, \beta_b, (V_w - \dot{d}_{T_{FA}}))$ and $F_{T_{SS}}(\omega, \beta_b, (V_w - \dot{d}_{T_{FA}}))$ introduce non-linearities in the model.

The turbine model has two control variables: the commanded generator torque T_{gc} , and the commanded blade pitch angle β_c . The dynamics of the generator is given as

$$\dot{Q}_g = \frac{1}{g_1} (T_{gc} - T - Q_g), \quad (4)$$

where coefficient g_1 represents the time-constant of the first-order dynamic model. The pitch dynamics is modeled as

$$\ddot{\beta}_b = -b_1 \dot{\beta}_b - b_2 (\beta_b - \beta_c). \quad (5)$$

Here, β_b represents the effective collective blade pitch angle and the coefficients b_{1-2} are model parameters representing properties of the pitch system second-order pitch model.

The reduced-order wind turbine model consists of eight system states,

$$\mathbf{x} = (\omega, d_{T_{FA}}, \dot{d}_{T_{FA}}, d_{T_{SS}}, \dot{d}_{T_{SS}}, \beta_b, \dot{\beta}_b, T_{gc}), \quad (6)$$

and two control input variables

$$\mathbf{u} = (\beta_c, T_{gc}). \quad (7)$$

The wind speed V_w is considered as a disturbance input to the model, i.e.

$$\mathbf{d} = (V_w). \quad (8)$$

The reduced-order model outputs the wind turbine electrical power

$$P_{gen} = \eta_{gen} \omega Q_g, \quad (9)$$

and the tower-base stresses

$$\sigma_{FA/SS} = t_1 d_{T_{FA/SS}} \quad (10)$$

in the fore-aft and side-side directions, modeled as linear functions of the respective tower-top deflections. Here, η_{gen} denotes the drivetrain conversion efficiency, and t_1 is a constant of proportionality derived from the tower-base geometry and material properties.

2.2 Data-driven correction

With advancements in computing technologies, machine learning techniques – including supervised and unsupervised learning – have become highly effective for a wide range of data-driven system identification tasks. A key advantage of supervised

175 learning over unsupervised learning is its access to both input states and their corresponding target states during training. This allows the model to generalize and predict system behavior for previously unseen input combinations. A particularly effective approach for supervised learning in this context is based on the training of a neural network (NN). NNs can approximate arbitrarily complex functions while also providing gradients, making them especially well-suited for integration within an optimal control framework.

180 In this work, the NN is designed to ~~establish~~ provide a static mapping from inputs to outputs. The ~~structure of an NN network architecture~~ consists of multiple hidden layers and a single output layer, ~~where each layer contains with each layer composed of~~ a certain number of neurons. ~~These neurons are~~ Each neuron is defined by weights, biases, and ~~activation functions~~ an activation function. Within a given layer, the input data is first ~~processed~~ transformed by applying the ~~corresponding~~ weights and biases ~~to each associated with the~~ neuron. The ~~transformed data is then passed on~~ resulting weighted sums are then passed to the
 185 next layer ~~based on~~ through the selected activation function. Activation functions apply a nonlinear mapping to the weighted input plus bias, which determines whether and to what extent a neuron is activated, thereby enabling the network to model complex, nonlinear relationships between inputs and outputs. The choice of activation function ~~plays a crucial~~ therefore plays a key role in shaping ~~how information flows~~ the flow of information through the network ~~and, consequently, its predictive performance. Moreover, for use within an ENMPC, the activation function must be continuous and differentiable, so that first-~~
 190 ~~and second-order derivatives can be computed. These derivatives are required for the numerical solution of the underlying optimization problem by gradient-based methods (Rawlings et al., 2017).~~

A feed-forward NN with one hidden layer and one output layer is considered in this work. The static mapping of the input features \mathbf{x}_{NN} to the output features \mathbf{y}_{NN} for the considered NN can be written as

$$\mathbf{y}_{\text{NN}} = \mathbf{f}_y^{\text{act}}(\mathbf{W}_y^T \mathbf{f}_h^{\text{act}}(\mathbf{W}_h^T \mathbf{x}_{\text{NN}} + \mathbf{b}_h) + \mathbf{b}_y). \quad (11)$$

195 Here, \mathbf{W} , \mathbf{b} , and $\mathbf{f}^{\text{act}}(\cdot)$ represent the weights, biases, and activation functions, respectively, where the subscript h denotes the hidden layer and the subscript y denotes the output layer.

Before training the NN, the generated dataset is split into training and testing sets. Moreover, every feature in the input and the target set is normalized by subtracting the minimum of the feature vector from the feature vector itself, and then dividing the result by the range (difference of maximum and minimum), i.e.:

$$200 \quad \mathbf{y}_{\text{NN}} = \frac{\mathbf{y}_{\text{NN}} - \mathbf{y}_{\text{NN}}^{\min}}{\mathbf{y}_{\text{NN}}^{\max} - \mathbf{y}_{\text{NN}}^{\min}}. \quad (12)$$

Furthermore, the normalized datasets are shuffled to reduce the possible clustering of conditions that might create biases. After pre-processing the training set, the parameters \mathbf{p} of the NN, defined as

$$\mathbf{p} = (\mathbf{W}_h, \mathbf{b}_h, \mathbf{W}_y, \mathbf{b}_y), \quad (13)$$

are computed using the Levenberg-Marquardt algorithm to minimize the sum of squares of error between the predicted output
 205 and target output.

The accuracy of NN predictions heavily depends on the quality of its training process, which requires a comprehensive dataset of inputs and corresponding target outputs. ~~Here data is obtained using a~~ Wind turbine original equipment manufacturers

(OEMs) typically have validated high-fidelity models from design and prototyping that can generate representative datasets, and they may also have access to high-resolution data from on-board sensors of operational turbines to supplement them. In the present work, data is obtained from a high-fidelity simulation model, using both standard measurements and estimates derived from them—these measurements.

Figure 1 illustrates the proposed approach of acquiring input and target data for NN training, where the solid blue circles represent the plant states $\mathbf{x}_i^{\text{Plant}}$ at a given time instant i . To generate training data, the ROM is initialized with each Plant state sample, setting $\mathbf{x}_i^{\text{ROM}} = \mathbf{x}_i^{\text{Plant}}$. The ROM then predicts the next state $\mathbf{x}_{i+1}^{\text{ROM}}$, based on the applied control inputs $\mathbf{u}_i^{\text{Plant}}$ and the influence of external disturbance $\mathbf{d}_i^{\text{Plant}}$.

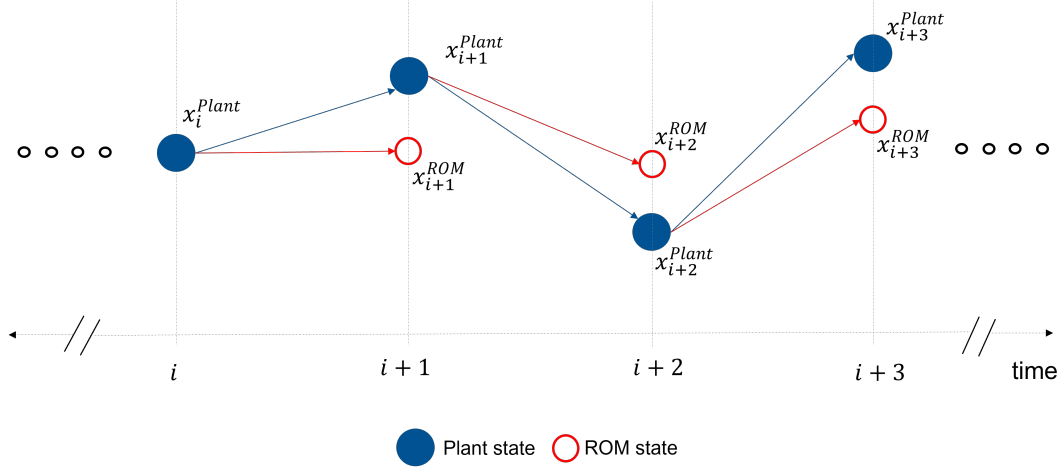


Figure 1. Data acquisition for model adaptation.

The corresponding error between the derivatives of the ROM model and the plant is defined as

$$\mathbf{e}_{i+1} = \dot{\mathbf{x}}_{i+1}^{\text{Plant}} - \dot{\mathbf{x}}_{i+1}^{\text{ROM}}, \quad (14)$$

and constitutes the target dataset. The derivatives are calculated using the current state $\mathbf{x}_i^{\text{Plant}}$ at time t_i and the corresponding next states $\mathbf{x}_{i+1}^{\text{Plant}}$ and $\mathbf{x}_{i+1}^{\text{ROM}}$ at time t_{i+1} via finite differences, i.e. $(\mathbf{x}_{i+1} - \mathbf{x}_i)/(t_{i+1} - t_i)$. The set of the current states, control inputs, and disturbances applied to the plant, constitute the input dataset $(\mathbf{x}_i^{\text{Plant}}, \mathbf{u}_i^{\text{Plant}}, \mathbf{d}_i^{\text{Plant}})$ for the i th time sample. This simple temporal discretization, although of limited numerical accuracy, is deemed sufficient for the present application, where modeling errors are typically larger than the numerical ones.

3 ENMPC formulation

The ENMPC is formulated based on the augmented internal model ROM_{aug} , as expressed by Eq. (1), to predict the system states and associated outputs over a short future horizon T_{horizon} . The discretization of time-continuous variables is performed over control time steps N_u in the prediction horizon. The duration of one control interval can thus be denoted as using N_u

control time steps of duration $T_{\text{ctrl}} = T_{\text{horizon}}/N_u$. ~~These predictions~~ The predictions of states and outputs are used to calculate ~~optimal control variables by optimizing a desired realistic and~~ control inputs that optimize a desired meaningful economic objective function (here chosen as profit, with the goal of balancing revenue and costs). Moreover, constraints are enforced to the optimization problem to ensure that the controller keeps the ~~controller should keep the~~ plant states and applied inputs within feasible ranges, ~~which are specified as optimization constraints.~~

The proposed ENMPC optimization problem ~~can be is~~ formulated as

$$\min_{\mathbf{u}, \xi} \underbrace{-(J_{\text{generation}}^{\text{Power}})^2 + (J_{\text{tower fatigue}}^{\text{FA}})^2 + (J_{\text{tower fatigue}}^{\text{SS}})^2 + \int_{t_0}^{t_0 + T_{\text{horizon}}} (W_1^\xi \xi_1^2 + W_2^\xi \xi_2^2) dt,}_{\text{red line}}$$

$$235 \quad \min_{\mathbf{u}, \xi} \underbrace{-(J_{\text{generation}}^{\text{Power}})^2 + (J_{\text{tower fatigue}}^{\text{FA}})^2 + (J_{\text{tower fatigue}}^{\text{SS}})^2 + \int_{t_0}^{t_0 + T_{\text{horizon}}} (W_1^\xi \xi_1^2 + W_2^\xi \xi_2^2) dt,}_{\text{blue wavy line}} \quad (15a)$$

subject to (15b)

$$\dot{\mathbf{x}}_c = \mathbf{F}_{\text{ROM}_{\text{aug}}}(\mathbf{x}_c, \mathbf{u}, \mathbf{d}, \mathbf{p}), \quad (15c)$$

$$\underline{\mathbf{u}} \leq \mathbf{u} \leq \bar{\mathbf{u}}, \quad (15d)$$

$$\underline{\mathbf{x}} \leq \mathbf{x} \leq \bar{\mathbf{x}}, \quad (15e)$$

$$240 \quad \underline{\xi} \leq \xi \leq \bar{\xi}, \quad (15f)$$

$$\underline{\dot{Q}}_g \leq \dot{Q}_g \leq \bar{\dot{Q}}_g. \quad (15g)$$

~~subject to~~

$$\underline{\dot{\mathbf{x}}} = \mathbf{F}_{\text{ROM}_{\text{aug}}}(\mathbf{x}, \mathbf{u}, \mathbf{d}, \mathbf{p}),$$

$$245 \quad \underline{\mathbf{x}}_c \leq \mathbf{x}_c \leq \bar{\mathbf{x}}_c,$$

$$\underline{\mathbf{u}} \leq \mathbf{u} \leq \bar{\mathbf{u}},$$

$$\underline{\xi} \leq \xi \leq \bar{\xi},$$

250 ~~and~~

$$\underline{\dot{T}}_g \leq \dot{T}_g \leq \bar{\dot{T}}_g.$$

The ~~optimization variables~~ meaning of all variables and terms in this problem are explained in Sects. 3.1 through 3.3.

3.1 Optimization variables

The optimization variables in the problem expressed by Eqs. (15) are the control variables $\mathbf{u} = (\beta_c, T_{gc})$ inputs $\mathbf{u} = (\beta_c, Q_{gc})$ and the slack variables $\xi = (\xi_1, \xi_2)$. The purpose of introducing slack variables is to achieve recursive feasibility of the MPC optimization problem in the presence of model uncertainties and system perturbations (S. Gros, 2013). Hence, in the present formulation, the state variable ω and the wind turbine electrical power output

$$P_{\text{gen}} = \eta_{\text{gen}} \omega T_g$$

output variable P_{gen} are augmented using the bounded slack variables ξ_1 and ξ_2 , respectively, where η_{gen} denotes the drivetrain conversion efficiency. This approach is used because ω , despite the smoothing effect provided by the large rotor inertia, is subject to wind perturbations and model errors that affect the economic MPC problem (S. Gros, 2013). The modified set of states \mathbf{x}_c can be expressed as is expressed as

$$\mathbf{x}_c = (\omega + \xi_1, d_{T_{\text{FA}}}, T_{\text{FA}}, d_{T_{\text{SS}}}, T_{\text{SS}}, \beta_b, \dot{\beta}_b, T_{Q_g}, \eta P_{\text{gen}} \omega T_g + \xi_2). \quad (16)$$

3.2 Optimization objective

The optimization objective aims to maximize the generated profit by balancing maximizing the revenue accrued from wind power generation and minimizing the cost incurred due to fatigue damage. The cost of fatigue damage should be expressed by appropriate models, which will differ depending on the component; for example, it is reasonable to assume that the effects of cyclic loading on a pitch bearing will in general be very different from the ones on a gearbox. Here, for the lack of specific models and relevant data, we simply consider the tower as an exemplary component that is often fatigue critical. It is clear that this is only an academic example, and more realistic scenarios could be readily developed by using the same methodology for multiple components, by using dedicated component-specific cost models.

The wind power generation is maximized by considering the aerodynamic power capture

$$J_{\text{generation}}^{\text{Power}} = w_P \int_{t_0}^{\underline{t_{\text{end}} t_0 + T_{\text{horizon}}}} (\omega T_Q Q_a(\omega, \beta_b, (V_w - \dot{d}_{T_{\text{FA}}})) dt, \quad (17)$$

where w_P denotes the revenue rate for providing electricity to the grid. It should be noted that even though revenue is accrued based on the overall electrical power generation, in this work the aerodynamic power is maximized. This is to avoid the greedy extraction of rotor kinetic energy by MPC (referred to as “turnpike effect” in S. Gros (2013)).

In general, the revenue rate w_P depends on time, because time-dependent ambient conditions influence the energy mix and because market prices may vary dynamically. However, the typical time scales of these variations are much longer – usually on the order of tens of minutes, and specifically 15 minutes in intra-day markets – than the receding horizon used in MPC, which typically spans only a few seconds. For this reason, even though w_P appears outside the integral in Eq. (17), the present formulation remains fully applicable to variable electricity prices.

The tower cyclic fatigue damage is minimized by a direct penalization of fatigue via the PORFC approach. The PORFC algorithm uses a pre-processing step to identify fatigue cycles c for a given set of stress samples σ , and splits the respective

285 cyclic fatigue damages over the contributing samples. In the general case, a particular stress sample may belong to no cycle
 (when it is not an extremum), may belong to one cycle (when it is part of only one half or full cycle), or to two cycles (when
it lies at a cycle-junction point) (Shi et al., 2018, 2019). The output of the pre-processing step is the PORFC mean parameters
 $\sigma_{m,c}^{\text{PORFC}}$ and PORFC weight parameters $\sigma_{w,c}^{\text{PORFC}}$ (Loew et al., 2021).

A Python script to extract the PORFC parameters for a given set of stress trajectories is shared with this work (Anand and
 Bottasso, 2025). This allows for a detailed understanding of the novel formulation and its adaptability and usage for economic
 290 MPC. The script performs standard rainflow counting to identify cycle characteristics and extract PORFC parameters. These
 parameters are then used to reformulate the cycle amplitudes and weights over stress samples in a continuous manner.

The cost of tower fatigue damage $J_{\text{tower fatigue}}^{\text{FA}}$, due to tower root fore-aft cyclic stress σ_{FA} , is formulated as

$$J_{\text{tower fatigue}}^{\text{FA}} = \frac{1}{T_{\text{ctrl}}} \int_{t_0}^{t_{\text{end}}} \sum_{c=1}^2 J_{c,\sigma_{\text{FA}}}^{\text{PORFC}}(\sigma_{\text{FA}}, \sigma_{\text{FA}m,c}^{\text{PORFC}}, \sigma_{\text{FA}w,c}^{\text{PORFC}}) dt,$$

$$295 \quad J_{\text{tower fatigue}}^{\text{FA}} = \frac{1}{T_{\text{ctrl}}} \int_{t_0}^{t_0+T_{\text{horizon}}} \sum_{c=1}^2 J_{c,\sigma_{\text{FA}}}^{\text{PORFC}}(\sigma_{\text{FA}}, \sigma_{\text{FA}m,c}^{\text{PORFC}}, \sigma_{\text{FA}w,c}^{\text{PORFC}}) dt, \quad (18a)$$

$$J_{c,\sigma_{\text{FA}}}^{\text{PORFC}} = \sigma_{\text{FA}w,c}^{\text{PORFC}} a_m \sigma_{\text{FA}eq,c}^m, \quad (18b)$$

$$\sigma_{\text{FA}eq,c} = |\sigma_{\text{FA}} - \sigma_{\text{FA}m,c}^{\text{PORFC}}| \frac{R_m}{R_m - \sigma_{\text{FA}m,c}}. \quad (18c)$$

$$J_{c,\sigma_{\text{FA}}}^{\text{PORFC}} = \sigma_{\text{FA}w,c}^{\text{PORFC}} a_m \sigma_{\text{FA}eq,c}^m,$$

300

$$\sigma_{\text{FA}eq,c} = |\sigma_{\text{FA}} - \sigma_{\text{FA}m,c}^{\text{PORFC}}| \frac{R_m}{R_m - \sigma_{\text{FA}m,c}}.$$

Here, a_m denotes the capital cost of the component and is determined from the initial capital expenditure of the machine (see
 also Loew et al. (2023) for details), R_m denotes the ultimate tensile strength of the material, and m represent the positive
 exponent derived from the material S-N characteristic.

305 The tower cyclic fatigue damage $J_{\text{tower fatigue}}^{\text{SS}}$, due to tower root side-side cyclic stress σ_{SS} , is formulated in a similar manner.

Although the optimization objective, shown in Eq. (15a), separately considers the costs of tower fore-aft and side-side
 fatigue, the final evaluation is based on the projected total cost, as explained below. In addition to the fact that fore-aft and
 side-side components depend on wind direction, which is not constant, this also ensures that any potential increase or decrease
 in tower side-side stress oscillations, resulting from control actions aimed at minimizing tower fore-aft stress (and vice-versa),
 310 is properly accounted for.

To obtain the cost of cyclic fatigue damage for each projection at a given azimuth direction on a tower section, the following
 steps are taken. First, rainflow counting is performed on the projected stress trajectory. Then, the Goodman equation is applied

for mean stress correction. The damage cost of each stress cycle is determined using the S-N curve of the material of the tower and the component cost. Finally, the Miner-Palmgren algorithm is used to sum the costs of individual cycles and obtain the total cost (refer to Loew et al. (2023) for a detailed ~~formulation~~description of this formulation).

This approach – here illustrated for the tower – is readily generalized to other components. Once cyclic fatigue is assessed on each prediction horizon for each component of interest, a dedicated model could provide failure rates and/or maintenance activities resulting from such loading, in turn generating the associated costs, which would be included in the optimization merit function.

3.3 Optimization constraints

~~The ENMPC optimization problem is subjected to the system dynamics of the augmented plant model $\text{ROM}_{\text{aug}}(\cdot)$. It should be noted that the objective terms of the optimization problem are not assigned arbitrary or heuristic weights. Instead, each term is weighted according to its actual economic value. As a result, the optimization outcomes are economically meaningful and directly aligned with practical decision-making considerations, rather than being influenced by ad-hoc tuning of weights. For instance, the weighting term to calculate revenue due to power production is represented by the (optionally time-varying) revenue rate w_P , as shown in Eq. (15e), to the inequality constraints on modified system states (17). Similarly, the cost due to accumulated tower fatigue damage is weighted using the initial capital-cost parameter a_m through the online rainflow analysis, as shown in Eq. (15d), and to the box constraints on control and slack variables, as shown in (18).~~

3.3 Optimization constraints

The ENMPC optimization problem expressed by Eqs. (15) is subjected to various constraints.

The equality constraints expressed by Eq. (15c) enforce the governing equations of the augmented plant model $\text{ROM}_{\text{aug}}(\cdot)$, and have the role of informing the problem of the underlying system dynamics.

The optimization is also subjected to inequality constraints. To ensure feasible states and control inputs, box constraints are provided through Eq. (15f) and (15d) and (15f), respectively. Slack variables are bounded using Eq. (15e). ~~Furthermore to ease convergence. Finally,~~ the rate of change of generator torque \dot{T}_g is also subjected to an inequality constraint, as shown in \dot{Q}_g is bounded using Eq. (15g), ~~to reduce the torque travel as well as the~~ to reduce torque travel and fatigue in the wind turbine drive-train.

3.4 State estimator Estimators

3.4.1 State estimator

The controller-internal model is initialized using the currently measured initial states \mathbf{x}_0 . However, not all system states of the internal model can actually be measured directly on the plant using standard on-board sensors. For instance, both the tower-top deflection and velocity states $(d_{T_{FA}}, \dot{d}_{T_{FA}}, d_{T_{SS}}, \dot{d}_{T_{SS}})$ for ROM and ROM_{aug} can not be measured directly on a real turbine. Only the rotor speed ω , the blade pitch angle β_b , and the tower-top accelerations $\ddot{d}_{T_{FA}}$ and $\ddot{d}_{T_{SS}}$ can be measured by onboard sensors,

whereas the remaining states need to be estimated using measured quantities. Furthermore, as the controller-internal model is only a reduced representation of the plant, the initial values measured directly on the plant may not be suitable for initializing the ENMPC. As a consequence, a state estimator is additionally required to provide initial value estimates \mathbf{x}_{est} of the system states for the ENMPC internal model, using the available measurements from the plant.

A classical approach for state estimation is the Kalman filter, also widely used for wind turbine control (Bottasso and Croce, 2009; Ritter, 2020). However, due to the nonlinear nature of the system and the need to enforce constraints on both stage and terminal states, here we instead adopt a moving horizon estimator (MHE). A detailed comparison between optimization-based state estimation techniques based on MHE and Kalman filters has been presented in Loew and Bottasso (2022). The MHE formulation used in this study builds upon the approach discussed in Anand et al. (2022).

MHE utilizes the system information from the plant over a finite past duration (specified using the MHE horizon length $T_{\text{horizon,est}}$), to calculate the initial state estimates $\mathbf{x}_{\text{est}}(t_0)$ for the current ENMPC step. The MHE optimization problem aims to minimize the is formulated as

$$\min_{\bar{\nu}} \int_{t_0 - T_{\text{horizon,est}}}^{t_0} (\|\mathbf{x}_{\text{est}} - \mathbf{x}_{\text{est,prev}}\|_{\mathbf{W}_{\text{prev}}}^2 + \|\mathbf{y}_{\text{est}} - \mathbf{y}_{\text{meas}}\|_{\mathbf{W}_{\text{meas}}}^2 + \|\bar{\nu}\|_{\mathbf{W}_{\bar{\nu}}}^2) dt, \quad (19a)$$

subject to (19b)

$$\dot{\mathbf{x}}_{\text{est}} = \mathbf{F}_{\text{est}}(\mathbf{x}_{\text{est}}(t), \mathbf{d}_{\text{est}}(t)) + \bar{\nu}(t). \quad (19c)$$

The objective function is represented by the weighted sum of the deviation of the current estimated output \mathbf{y}_{est} from the measurement values \mathbf{y}_{meas} , with the deviation of the current state estimates \mathbf{x}_{est} from the previous state estimates $\mathbf{x}_{\text{est,prev}}$ (squares of state and output deviations and of the noise variable $\bar{\nu}$ (S. Gros, 2013; Huang et al., 2010). The diagonal weighting matrices \mathbf{W}_{meas} , \mathbf{W}_{prev} , and $\mathbf{W}_{\bar{\nu}}$ are obtained by a trial and error tuning, such that a satisfactory performance is achieved.

The role of the state deviation term is to ensure a smooth estimator output over consecutive MHE steps), and with the noise variable $\bar{\nu}$ (S. Gros, 2013; Huang et al., 2010).

The objective function is given as-

$$\min_{\bar{\nu}} \int_{t_0 - T_{\text{horizon,est}}}^{t_0} (\|\mathbf{y}_{\text{est}} - \mathbf{y}_{\text{meas}}\|_{\mathbf{W}_{\text{meas}}}^2 + \|\mathbf{x}_{\text{est}} - \mathbf{x}_{\text{est,prev}}\|_{\mathbf{W}_{\text{prev}}}^2 + \|\bar{\nu}\|_{\mathbf{W}_{\bar{\nu}}}^2) dt,$$

where $\mathbf{y}_{\text{est}} = (\mathbf{x}_{\text{est}}, \ddot{d}_{T_{\text{FA,est}}}, \ddot{d}_{T_{\text{SS,est}}})$ and $\mathbf{y}_{\text{meas}} = (\mathbf{x}_{\text{meas}}, \ddot{d}_{T_{\text{FA,meas}}}, \ddot{d}_{T_{\text{SS,meas}}})$ estimated and measured outputs are respectively defined as $\mathbf{y}_{\text{est}} = (\mathbf{x}_{\text{est}}, \ddot{d}_{T_{\text{FA,est}}}, \ddot{d}_{T_{\text{SS,est}}})$ and $\mathbf{y}_{\text{meas}} = (\mathbf{x}_{\text{meas}}, \ddot{d}_{T_{\text{FA,meas}}}, \ddot{d}_{T_{\text{SS,meas}}})$. The estimated tower-top fore-aft acceleration $\ddot{d}_{T_{\text{FA,est}}}$ and side-side acceleration $\ddot{d}_{T_{\text{SS,est}}}$ are obtained using the nonlinear output equation expressed by Eq. (3a) and Eq. (3b), respectively. The measured tower-top fore-aft acceleration $\ddot{d}_{T_{\text{FA,meas}}}$ and the side-side acceleration $\ddot{d}_{T_{\text{SS,meas}}}$ are obtained from the plant as a result of standard sensor measurements. The measured tower-top velocity and deflection in both the fore-aft and side-side directions are obtained by numerical integration of the tower-top acceleration and velocity, respectively. The diagonal weighting matrices \mathbf{W}_{meas} , \mathbf{W}_{prev} , and $\mathbf{W}_{\bar{\nu}}$ are obtained by a trial and error tuning, such that a satisfactory performance is achieved.

The optimization problem is subjected to the ~~estimator system dynamics~~

$$375 \quad \dot{\mathbf{x}}_{\text{est}} = \mathbf{F}_{\text{est}}(\mathbf{x}_{\text{est}}(t), \mathbf{d}_{\text{est}}(t)) + \boldsymbol{\nu}(t),$$

where ~~$\mathbf{d}_{\text{est}}(t) = (V_w(t), \beta_b(t), T_g(t))$~~ equality constraints expressed by Eq. (19c), which inform the estimator of the underlying system dynamics. In Eq. (19c), ~~$\mathbf{d}_{\text{est}}(t) = (V_w(t), \beta_b(t), Q_a(t))$~~ are the disturbance inputs to the system, which are already set by the ENMPC and are hence fixed for the current MHE step. Here, \mathbf{x}_{est} represents the estimator system states, corresponding to the wind turbine system states \mathbf{x} , as discussed in Sect. 2.1. Moreover, $\mathbf{F}_{\text{est}}(\cdot)$ represents the system of ODEs for wind turbine dynamics discussed in Sect. 2.1.

After the execution of an MHE step, the terminal state at the end of the MHE horizon becomes the initial state at the beginning of the ENMPC prediction horizon, i.e. ~~$\mathbf{x}_0 = \mathbf{x}(t_0) = \mathbf{x}_{\text{est}}(t_0)$~~ ~~$\mathbf{x}_0 = \mathbf{x}(t_0) = \mathbf{x}_{\text{est}}(t_0)$~~ .

3.5 Disturbance estimator

3.4.1 Disturbance estimator

385 The wind speed V_w is considered as a disturbance input to the ENMPC formulation, and needs to be estimated over the prediction horizon T_{horizon} of the controller. This work considers a simple rotor effective wind speed (REWS) estimator, based on the approach discussed in Soltani et al. (2013). The REWS estimator utilizes the drivetrain dynamics, ~~see expressed by~~ Eq. (2), to estimate the aerodynamic torque ~~as~~

$$\frac{T_Q Q_a}{\omega_{\text{meas}}}_{\text{est}} = \frac{P_{Q_{\text{est}}}}{\omega_{\text{meas}}} \approx \frac{P_{\text{gen}_{\text{meas}}} + J_r \dot{\omega}}{\omega_{\text{meas}}}, \quad (20)$$

390 ~~using where~~ ~~$P_{\text{gen}_{\text{meas}}}$~~ is the measured generator power ~~and rotor speed and~~ ~~ω_{meas}~~ ~~the measured rotor speed~~. The rate of change of rotor speed $\dot{\omega}$ is computed by finite difference from ω_{meas} . The estimated aerodynamic torque ~~$T_{Q_{\text{est}}} Q_{a_{\text{est}}}$~~ is then equated to the aerodynamic torque ~~$T_Q(\omega_{\text{meas}}, \beta_{b_{\text{meas}}}, V_{w_{\text{est}}}) Q_a(\omega_{\text{meas}}, \beta_{b_{\text{meas}}}, V_{w_{\text{est}}})$~~ described in Sect. 2.1, to estimate wind speed $V_{w_{\text{est}}}$, for the measured pitch angle $\beta_{b_{\text{meas}}}$ and ω_{meas} .

4 Results and discussions

395 4.1 Case study

The ability of the adapted model to accurately predict the plant states depends directly on the precision of the data-driven corrections. Additionally, to determine the extent of model adaptation required, it is necessary to assess how reducing the model mismatch ~~impacts influences~~ the closed-loop performance of the controller. To answer these questions, we consider a plant represented by the NREL 5 MW reference wind turbine (Jonkman et al., 2009), which is modeled using OpenFAST
400 (Bonnie Jonkman et al., 2022), a widely used tool for simulating wind turbine dynamics.

The plant model includes the first and second flapwise ~~bending modes~~ and the first edgewise bending ~~mode~~ modes for each of the three blades. Additionally, it also includes the first and second tower bending modes in both fore-aft and side-side directions, as well as the torsional flexibility of the drivetrain and the generator DOF.

405 The model, which incorporates pitch and torque actuators but excludes the yaw mechanism, consists of thirty-three system states. There are eight states for the tower dynamics, eighteen for the blades (six per blade), two for drive-shaft torsion, two for rotor rotation, two for collective blade pitch actuation, and one for generator torque actuation.

The fixed model parameters of the corresponding ROM, namely f_{1-3} , s_{1-4} , g_1 , ~~and~~ b_{1-2} , and t_1 , are derived from the NREL report describing the 5 MW reference wind turbine (Jonkman et al., 2009). Table 1 summarizes these parameters and lists their corresponding values.

Table 1. ROM parameters derived from the 5 MW reference wind turbine report and OpenFAST baseline-controller simulations (Jonkman et al., 2009).

<u>Parameter</u>	<u>Equation</u>	<u>Value</u>	<u>Unit</u>
J_r	(2)	4.0470e7	kg m ²
f_1, f_2, f_3	(3a)	4.3218e5, 1.7596e4, 1.7911e6, 1.947e4	kg, kg s ⁻¹ , kg s ⁻²
s_1, s_2, s_3, s_4	(3b)	4.3218e5, 1.7596e4, 1.7911e6, 1.947e4	kg, kg s ⁻¹ , kg s ⁻² , kg m ⁻²
g_1	(4)	0.01	s
b_1, b_1	(5)	0.01	s ⁻¹ , s ⁻²
η_{gen}	(9)	0.944	~
t_1	(10)	245.76	MPa m ⁻¹

410 4.1.1 Data generation

The performance of a NN heavily depends on the quality of its training, which requires an exhaustive dataset that encompasses a wide range of operating conditions. To generate a comprehensive training dataset, the OpenFAST model is simulated in turbulent wind conditions using the baseline controller provided in the OpenFAST package. Full-field turbulent wind inputs are generated using TurbSim (Jonkman, 2009), considering the class-B normal turbulence model. Simulations are performed
415 for wind speeds ranging from cut-in to cut-out, in 1 ms⁻¹ steps. For each wind speed, six different turbulent wind seed simulations are conducted.

Figure 2 presents the Pearson correlation coefficients of the states (\mathbf{x}), inputs (\mathbf{u}), and disturbances (\mathbf{d}) of the ROM with the corresponding state errors (refer to Sect. 2.2), computed over the entire dataset. The Pearson correlation coefficient quantifies the linear relationship between two variables (Nafis Faizi and Yasir Alvi, 2023). Each entry in the table of Fig. 2 displays the

420 absolute value of the coefficient, where a higher magnitude indicates a stronger correlation. The same relationship is visualized through a color gradient map, where darker shades represent stronger correlations and lighter shades indicate weaker ones.

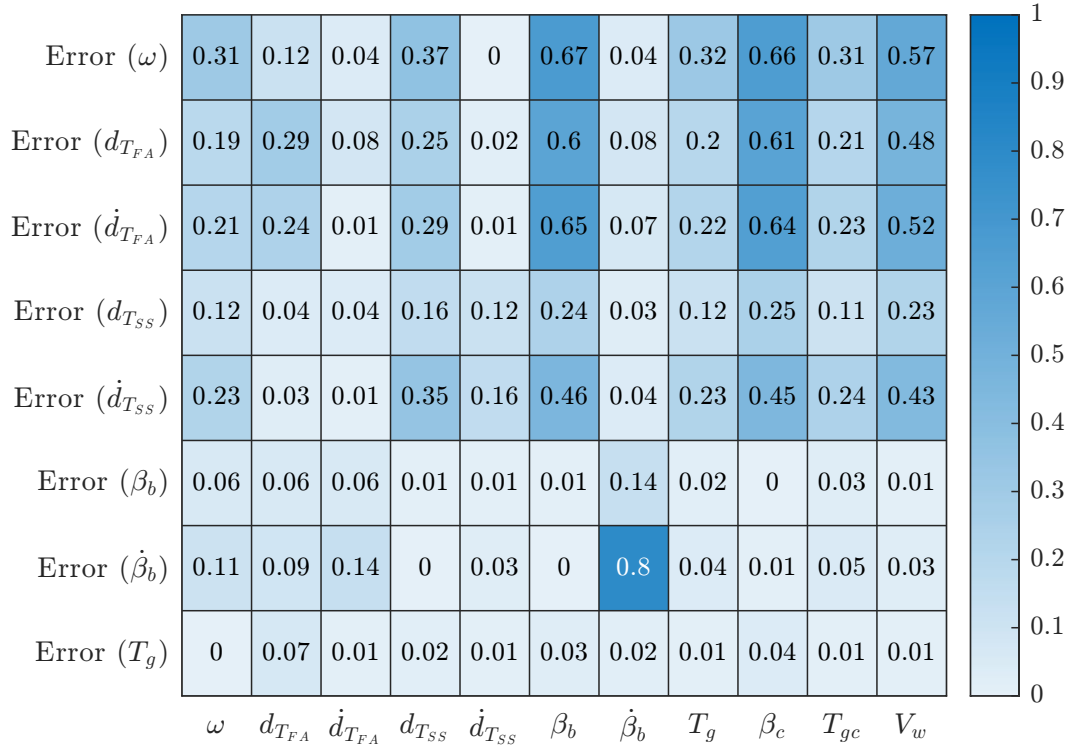


Figure 2. Correlation coefficient of states, inputs, and disturbance of the controller-internal model (as columns) with the error in states (as rows) for the generated dataset, rounded off to two significant digits. The number in each cell denotes the absolute value of the Pearson correlation coefficient, while the cell color visually denotes the degree of correlation.

Figure 2 shows that all ROM states and inputs significantly influence the state errors, as evidenced by their ~~nonzero~~non-zero correlation coefficients. In particular, the rotor speed (ω) and blade states ($\beta_b, \dot{\beta}_b$) exhibit the strongest correlation with both rotor speed errors and tower state errors. Additionally, the control inputs (β_c and $T_{gc}Q_{gc}$) and wind speed (V_w) strongly affect the mismatch across all states. Furthermore, the ~~nonzero~~non-zero yet distinct correlation magnitudes for blade pitch (β_b) and collective blade control (β_c) highlight the importance of blade dynamics, ~~shown in~~expressed by Eq. (5), in the internal model of the controller. This suggests that, while the ROM captures an approximation of the complex aeroelastic response, it does not fully represent the detailed dynamics present in the plant.

4.1.2 NN training

430 The proposed NN input set \mathbf{x}_{NN} contains eleven features (eight system states, two control variables, and one disturbance input), and each output set \mathbf{y}_{NN} contains eight features representing errors in the derivatives of states calculated using the plant and

ROM states. The selection of input features is guided by the correlation coefficients presented in Fig. 2, which indicate a ~~nonzero non-zero~~ correlation between all variables in the input and target sets. The hidden layer of the network consists of twenty neurons, each utilizing a radial basis activation function, while the output layer comprises eight neurons with linear
435 activation functions. The number of neurons in the hidden layer was determined through hyperparameter tuning, ensuring optimal training performance.

Before training the NN, the generated dataset is split into training and testing sets. During wind turbine operation, more data is naturally collected for operating conditions corresponding to more probable wind speed values. To account for this effect in the application of the proposed methodology, the dataset split is performed according to a hypothetical site-specific Weibull
440 distribution. Figure 3 illustrates the distribution of selected input features within the training dataset, ~~which consists of 216,071 sample points.~~

The various subplots in Fig. 3 show that the dataset covers a broad operational range of the wind turbine, allowing the NN to predict the target variables across a wide range of input conditions. Furthermore, Fig. 3i confirms that the wind speed distribution in the training dataset closely follows the Weibull shape, ensuring a realistic representation of operating conditions.

445 The training dataset consists of 216,071 sample points. This number is small compared to the number of data points typically generated for design load case (DLC) 1.2 of the IEC Standards 61400-1 applicable to wind turbine certification and testing (IEC, 2019), which – assuming 6 turbulence seeds and a sampling rate of 0.1 seconds – would result in 3,312,000 data points. This suggests that model adaption may be based on datasets that are one order of magnitude smaller than datasets routinely collected for standard design and certification purposes.

450 4.2 Open-loop evaluation

The ability of the augmented internal model to ~~accurately~~ track system states ~~is necessary~~ accurately is essential for ensuring both the optimality and the stability of the ~~closed-loop~~ closed-loop behavior. To evaluate this aspect of the proposed approach, both ROM_{aug} and ROM are simulated using each input combination from the testing dataset (refer to Sect. 4.1.2), with the initial state accordingly set. The final states predicted by both models are then compared to the corresponding plant states, and
455 the prediction error is computed to quantify the accuracy ~~of~~ achieved by each model.

Figure 4 presents the Kernel-density plot of the absolute prediction errors for both ROM (solid blue line) and ROM_{aug} (solid green line) across all system states. For each of the subplot, the x ~~axis~~ axis represents the absolute error values, while the y ~~axis~~ axis shows the probability density estimate (PDE), calculated using a normal kernel function.

In the ROM case, certain states, such as “Tower-top FA defl.” and “Tower-top FA vel.”, exhibit their highest PDE at a ~~nonzero~~ non-zero error value, indicating a mismatch in model fidelity. In contrast, in the ROM_{aug} case, this mismatch is corrected using the proposed adaptation scheme. As a result, the PDE peak shifts toward zero, signifying an improved state prediction accuracy. Furthermore, for most system states, the PDE peak magnitude in the ROM_{aug} case is higher than in the ROM case. This indicates a greater concentration of cases where ROM_{aug} achieves lower absolute errors than ROM, further demonstrating the effectiveness of the proposed model augmentation. The figure also shows that the accuracy of some quantities cannot be
465 improved, although their typical errors are always very small.

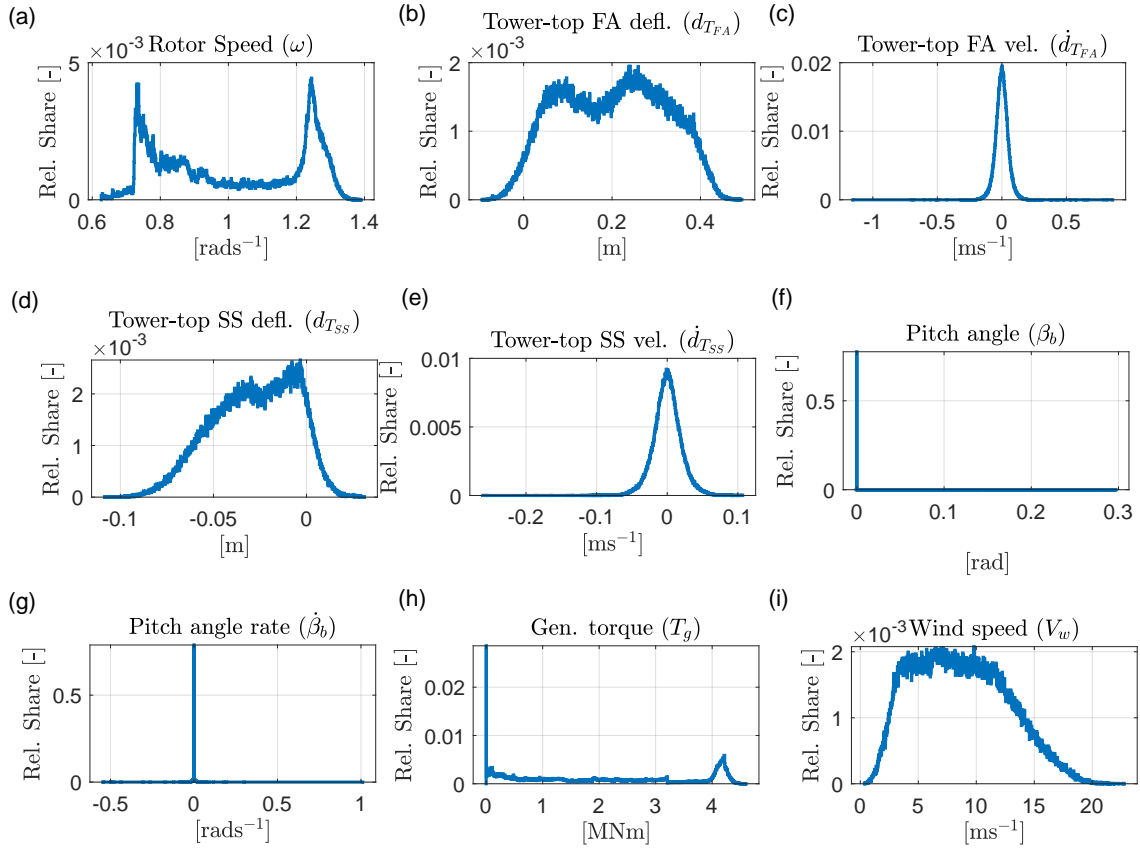


Figure 3. Distribution of different input features in the training set.

To quantify the effectiveness of ROM_{aug} in minimizing plant-model mismatch in open-loop, a statistical evaluation was conducted using the mean and standard deviation (STD) of prediction errors. Table 2 presents the percentage reduction in both the average error and standard deviation of errors error mean and STD for ROM_{aug} , relative to ROM, across the test set.

The results show varying degrees of improvement in state prediction, demonstrating that NN-based augmentation reduces not only the average error but also the error spread over different operating conditions. A greater reduction in prediction error is observed for states with higher absolute error magnitudes in Fig. 4. This highlights the effectiveness of weight tuning during the NN training stage, which prioritizes correcting states with significant errors. These findings further emphasize the effectiveness of the proposed offline data-driven approach in reducing plant-model mismatch, improving the overall accuracy of the internal model.

For a practical application of the model adaptation, it is interesting to quantify the amount of training data that is needed to achieve a desired level of performance. To this end, multiple data subsets are created from the original training set. Each subset contains a specified fraction of the data samples from the original training set.

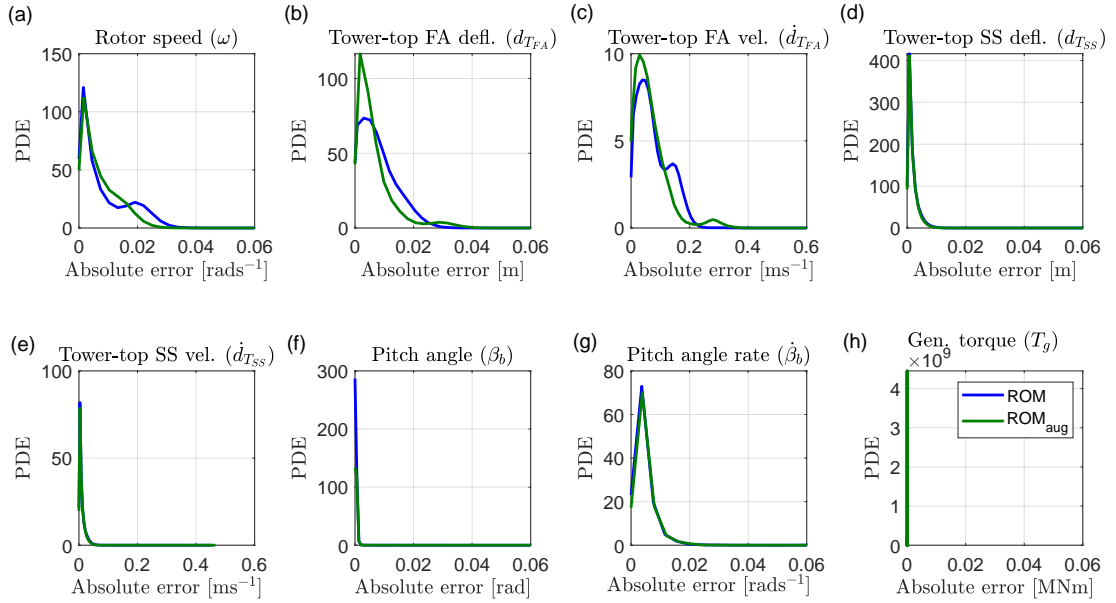


Figure 4. Probability density estimate (PDE) PDEs of the open-loop prediction errors for both ROM_{aug} and ROM, shown in green and blue, respectively, evaluated over the test set.

Table 2. Percentage reduction in mean error mean and standard deviation (STD) error due thanks to model augmentation, as assessed on the test set.

State	Mean error reduction [%]	STD error reduction [%]
Rotor speed (ω)	25.37	26.51
Tower-top FA defl. ($d_{T_{FA}}$)	20.55	12.57
Tower-top FA vel. ($\dot{d}_{T_{FA}}$)	11.02	9.73
Tower-top SS defl. ($d_{T_{SS}}$)	7.91	8.14
Tower-top SS vel. ($\dot{d}_{T_{SS}}$)	7.76	9.05
Pitch angle (β_b)	5.69	5.96
Pitch angle rate ($\dot{\beta}_b$)	0.08	0.53
Gen. torque (T_g)	0.01	0.00

Figure 5a illustrates the distribution of wind speed for multiple subsets, ranging from 45% to 95% of the original training set. The x -axis represents the wind speed magnitude, while the y -axis shows the corresponding relative share. Each subset is used to train a NN with the same architecture as described in Sect. 4.1.2.

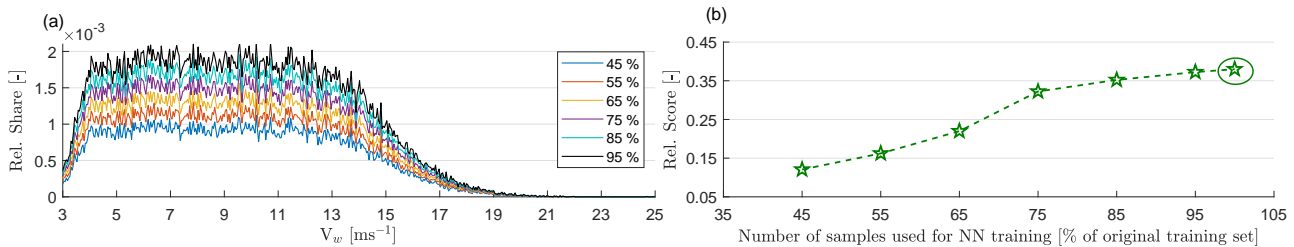


Figure 5. Open-loop evaluation of the proposed model adaptation where the NNs are trained using subsets of the full training set. Relative share of wind speed (V_w) in the NN training set (a). Corresponding performance score of ROM_{aug} relative to the performance score of ROM as a function of test set size (b).

Figure 5b presents the performance of the adapted models evaluated on the same test set. The performance score is calculated by summing the root mean squared error (RMSE) of predictions for all eight states. For ease of comparison, the y axis reports the performance scores of the different ROM_{aug} models, normalized against the performance score of ROM. The y -axis shows the relative values, while the x -axis displays the different ROM_{aug} formulations trained using the data subsets shown in Fig. 5a. Additionally, Fig. 5b includes axis displays the number of samples in percentage of the full training set. The figure also reports the normalized performance score of the ROM_{aug} model trained with the full dataset, represented by the green circle.

The results show that, as expected, incorporating more data into the training process provides the NN with additional information, leading to improved performance. However, even a relatively small subset of training data helps reduce the plant-model mismatch. Furthermore, performance begins to level off beyond a certain point, as additional data samples no longer significantly contribute to improving the model because they do not carry any extra useful informational content that is not already present in the data pool. In this study, performance starts to plateau once 85% of the training dataset is used. As noted earlier, even when using the full dataset, the number of data points that are necessary for model adaption is small compared to the typical datasets collected in standard aeroelastic analyses conducted during routine design and certification activities.

4.3 Closed-loop evaluation

Although the prediction errors of the augmented ROM are still non-zero for some operating conditions (refer to the long tail of the PDE plots in Fig. 4) indicate that the prediction errors of the augmented ROM remain non-zero for some operating conditions, it is useful to understand the impact of still useful to examine the potential benefit of reducing plant-model mismatch reduction on closed-loop performance, as this helps quantify the necessary level of compensation. To investigate this aspect

500 of the formulation, the proposed adaptive economic controller is implemented in ~~closed-loop~~ closed loop with the plant. This configuration ~~will be henceforth is~~ referred to as ENMPC_{aug}. To assess the impact of the augmentation, the ~~performance of the plant~~ plant performance is also evaluated using the same ENMPC formulation but based on the original, non-augmented ROM, ~~which is~~ referred to as ENMPC.

~~We consider the design load case (DLC)~~ Several studies on wind turbine control have demonstrated that economic MPC formulations yield superior performance compared to baseline controllers (Jonkman et al., 2009; Abbas et al., 2022), as well as standard, reference-tracking-based MPC formulations. This holds both for pure power-maximization objectives (Pustina et al., 2022; Hovgaard et al., 2022) and for combined power-maximization and fatigue-minimization objectives (Loew and Bottasso, 2022; Soleymani et al., 2024; Wang et al., 2024). Therefore, the discussion in this section focuses only on the closed-loop behavior of ENMPC and ENMPC_{aug} formulations, in order to quantify the performance improvement resulting from model adaptation.

510 We consider DLC 1.2 at 11 ms^{-1} wind speed. The ENMPC-MHE optimization problem (refer to Sect. 3) is solved via the state-of-the-art Acados framework (Robin Verschuere et al., 2019). The interior-point solver HPIPM is used for solving the underlying quadratic programs (QP) within the nonlinear program (NLP). Several sequential quadratic program (SQP) iterations are carried out at each controller step. The multiple shooting approach is employed with a Newton step length of 1. To address potential numerical issues caused by the highly non-standard formulation produced by PORFC (Loew et al., 2020b),
515 the Hessian matrix is automatically convexified. It is important to note that solving multiple SQPs can improve performance. However, it also increases the computational burden.

The ENMPC and MHE horizon lengths, T_{horizon} and $T_{\text{horizon,est}}$, are both set to 2 seconds, each having 20 discretization steps. This results in a sample time T_{ctrl} of 100 ms for both the controller and the estimator. The sample time of the plant, T_{sim} , is set to 10 ms. The optimal control inputs applied to the plant model are considered as piece-wise constant values over
520 T_{ctrl} . Measurements from the plant are taken every T_{ctrl} . Table 3 lists the fixed optimization parameters for the ENMPC. The weighting matrices for the MHE optimization are listed in Loew and Bottasso (2022).

The closed-loop simulations run for a duration of 10 minutes. Six turbulent wind speed seeds, generated using TurbSim, are used to characterize uncertainties in fatigue damage. The controller uses the estimated wind speed REWS (refer to Sect. 3.4.1) as input, which remains constant over the prediction horizon of the controller.

525 The closed-loop control performance is evaluated using the following performance indicators:

1. Revenue due to power generation, calculated considering a fixed feed-in tariff w_P and turbine electrical power generation $\eta_{\text{gen}} \omega T_g - \eta_{\text{gen}} \omega Q_g$ (refer to Eq. 17 for details).
2. Cost due to projected tower base fatigue damage. To calculate the projected damage, the tower fore-aft $\sigma_{\text{FA}}(t)$ and tower side-side oscillations $\sigma_{\text{SS}}(t)$ are first projected along the various azimuth directions at tower base. Next, the fatigue damage cost is computed for each of these projections, as discussed in Sect. 3.2. Finally, the maximum cost across all
530 projections is selected.
3. Profit, calculated as a the difference of revenue and cost.

Table 3. Fixed optimization parameters for closed-loop evaluation. The values are derived from Loew et al. (2023); Anand et al. (2022); Sutherland (1999); Jonkman et al. (2009).

Parameter	Equation	Value	Unit
W_1^ξ, W_2^ξ	(15)a	1e6, 1e6	-
\underline{x}_c	(15)c	0, -1.302, -1.302, 0, -0.1396, 0, 0	rad s ⁻¹ , m, m, rad, rad s ⁻¹ , MNm, MW
\bar{x}_c	(15)c	1.2671, 1.302, 1.302, 1.5708, 0.1396, 4.5981, 5	rad s ⁻¹ , m, m, rad, rad s ⁻¹ , MNm, MW
\underline{u}_c	(15)d	0, 0	rad, MNm
\bar{u}_c	(15)d	1.5708, 4.5981	rad, MNm
$\underline{\xi}, \bar{\xi}$	(15)e	-0.1, 0.1	-
\dot{Q}_g, \bar{Q}_g	(15)f	-1.4550, 1.4550	MNm s ⁻¹
w_P	(17)	0.2	€kWh ⁻¹
a_m	(18)b	4.00e6	€
m	(18)b	4	-
R_m	(18)c	400	MPa

4. Pitch travel, showing the total degrees that the blades traveled for a given control formulation. This can be considered as a proxy for the usage of pitch actuators, which may be prone to wear and tear, calling for extra maintenance.

545 5. Torque travel, showing the total amount of torque that the generator had to apply. This can be considered as a proxy for the usage of the turbine drivetrain, leading to wear and tear of bearings and gearbox. Additionally, it also serves as a proxy for switching-related damage in the power electronic converters.

4.3.1 Economic performance of the controller

Figure 6 presents the performance indicators calculated over a 10 minute simulation minutes, with results averaged across 540 different seeds. The set of bars in the left and right parts of the figure represent the performance for the ENMPC and ENMPC_{aug} formulations, respectively. The color of the bars corresponds to different performance indicators. The results for ENMPC_{aug} are normalized with the ENMPC ones to facilitate comparison, and the y -axis shows the relative values. The black numbers axis shows these relative values, which are also noted in black above each bar indicate the relative cumulative value compared to the ENMPC case. Additionally, the numbers on the face of each bar, shown in purple text, represent the absolute values.

545 The plots in Fig. 6 show Figure 6 shows that ENMPC_{aug} results in 9% higher economic profit than ENMPC. This improvement is due to the more accurate estimation of revenue and cost within ENMPC_{aug}, which is made possible by a better

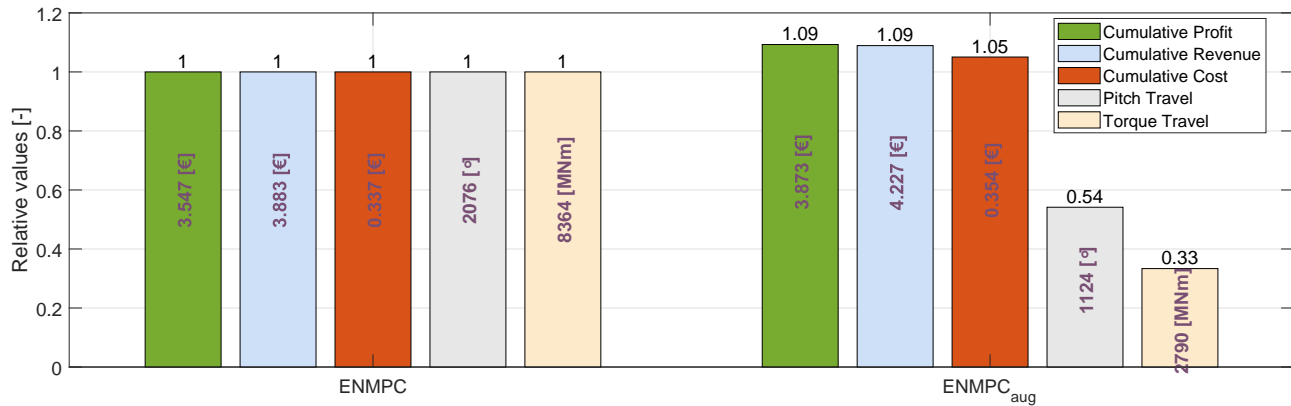


Figure 6. Performance indicators for ~~closed-loop~~ closed-loop simulations using controllers employing the baseline ROM (ENMPC) and the augmented ROM (ENMPC_{aug}) as internal models. The black numbers on the top of each bar denote the corresponding relative cumulative values. The purple text on the face of each bar denote the absolute cumulative values.

prediction of the system states. The higher profit is directly attributed to an increased revenue, with a slight increase in cost. Since the absolute economic value of revenue exceeds that of cost (as shown by the purple numbers on the face of the bars), ENMPC_{aug} effectively balances the two, leading to a higher overall economic profit.

550 In contrast, for the ENMPC case, while the controller aims to maximize economic profit, the plant-model mismatch leads to control actions that are not economically optimal. As a result, the controller struggles to accurately estimate and balance revenue and cost, ultimately resulting in a lower economic profit.

Furthermore, since the future predictions within the controller more closely match the actual evolution of the plant in the ENMPC_{aug} formulation, the controller requires less frequent control actions. This is reflected in the significantly smaller pitch and torque travel compared to the ENMPC case.

555 As a result, reducing plant-model mismatch to improve system state predictions ~~;~~ not only enhances performance but also leads to a substantial reduction in actuator usage. ~~This~~ It is reasonable to assume that this, in turn, ~~results will result~~ in lower maintenance costs for both the actuators and the drivetrain. This effect was however not quantified here, for a lack of data and ~~specific~~ of specific and reliable models.

560 4.3.2 Benefits under different wind inputs

Advanced wind turbine control formulations require the current wind speed as an input. Improved foresight of the wind speed enables the ENMPC to determine the most suitable control actions.

Wind speed can be gauged using a simple wind-speed estimator, as utilized in this work (refer to Sect. 3.4.1), or through advanced estimators as discussed in Soltani et al. (2013). Alternatively, the current wind speed can be measured directly, either

565 using a nacelle-mounted anemometer or a light detection and ranging (LiDAR) device. LiDARs not only provide real-time wind speed data but also offer short-term wind speed previews. This capability makes LiDARs an ideal complement to MPC-based wind turbine control, where the MPC optimization uses system states derived from wind speed forecasts over the MPC prediction horizon (Loew and Bottasso, 2022; Canet et al., 2021).

Here, the benefits of the proposed model adaptation for reducing plant-model mismatch under different wind input estimates
570 are assessed. Figure 7 presents various wind profiles used as input to the controller.

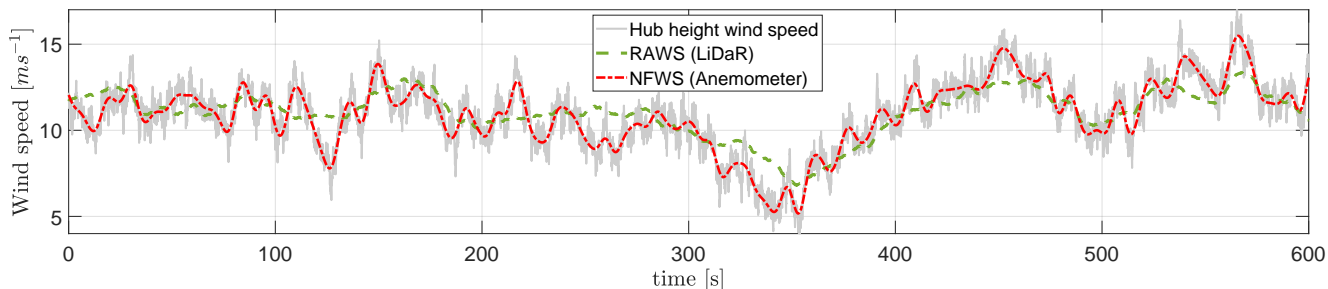


Figure 7. Exemplary wind profiles used as disturbance inputs to the ENMPC formulations.

The [solid](#) gray curve represents the longitudinal component of the full wind field generated using TurbSim at the turbine hub height for a 10 minute duration. This scenario is labeled as “Hub height wind speed”. This is only shown to illustrate wind fluctuations, but it is not used as input to the controller. The [dash-dotted](#) red curve corresponds to the nacelle filtered wind speed (NFWS), which is a rough approximation of what an anemometer mounted on the nacelle would measure. Typically,
575 anemometer measurements are subjected to various disturbances, including – among others – flow distortion due to proximity of the nacelle (a bluff body), periodic effects caused by blade passage, interference due to the wake, [and](#) sensor noise. For the lack of models of these complex phenomena, here we have simply filtered the wind field at the nacelle location using a standard bandpass filter. This case is referred to as “Anemometer”. The [dashed](#) green curve shows the rotor averaged wind speed (RAWS). The RAWS is a much simplified representation of what a nacelle-mounted scanning LiDaR system with
580 discrete scanning and spatial averaging would estimate under a frozen turbulence hypothesis, i.e. with a purely rigid transport of the flow from the measurement volume to the rotor disk (Loew and Bottasso, 2022). This case is referred to as “LiDaR”.

It can be observed that the anemometer-measured wind speed follows the highly turbulent fluctuations of the wind speed at hub height. Additionally, the RAWS shows even less dynamic variation in the wind speed but successfully captures the long-term wind speed trends. Although these speeds are only very rough approximations of the wind that could be actually measured
585 on a wind turbine, they still capture a range of situations from point-wise exact values to spatial and temporal averages.

Figure 8 presents the results [of obtained with](#) the closed-loop control formulations, considering different wind speed estimates. For each wind speed input scenario, two sets of bars are displayed: the first set represents the ENMPC case, [followed by](#) [the second set for while the second corresponds to](#) the ENMPC_{aug} case. Within each set, [each of](#) the five performance indicators

are shown as five bars, each distinguished by different face colors is shown as a bar of a different face color. The various sets of bars correspond to the following situations:

- The first and second sets show results when the controllers use REWS, described in Sect. 3.4.1, as disturbance input and the current wind speed is held constant over the prediction horizon. These results are the same as discussed in Fig. 6, and are shown here again for ease of comparison.
- The third and the fourth sets show results when the controllers use NFWS (Anemometer) as disturbance input, and the current wind speed is held constant over the prediction horizon.
- The fifth and the sixth sets show results when the controllers use LiDaR measurements as input, and the current wind speed is held constant over the prediction horizon.
- The seventh and the eighth sets show results when the controllers use LiDaR measurements as input, and a perfect preview of wind condition over the prediction horizon is considered. This case has been labeled as LiDaR-PF.

The results are normalized with respect to the ENMPC case, which is shown in the first set. The black text above each bar represents the relative cumulative values. To aid interpretation, the results from different wind input scenarios are highlighted with distinct background colors. The red background corresponds to the Anemometer scenario, the light green shade represents the LiDaR scenario, and the dark green background indicates the LiDaR-PF scenario.

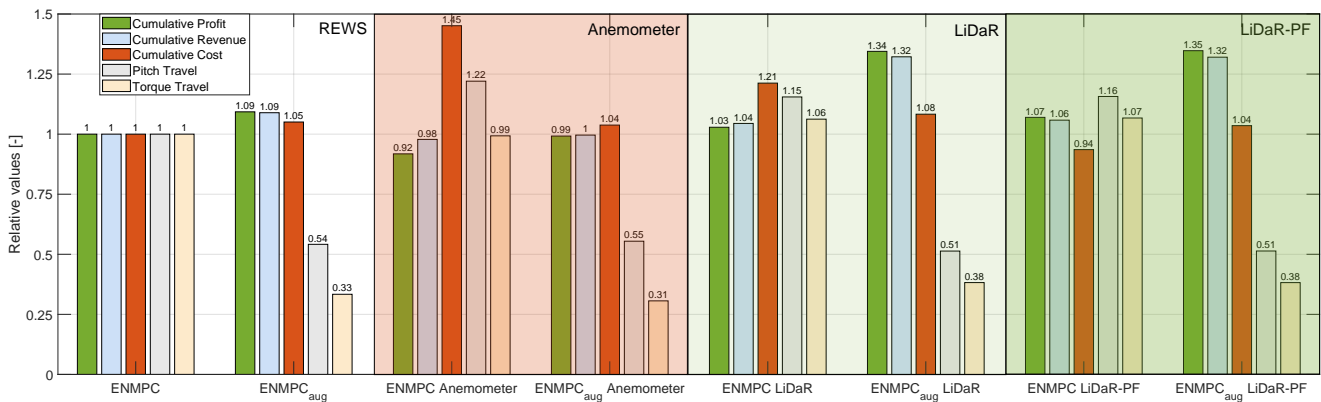


Figure 8. Performance indicators for closed-loop-closed-loop simulations using ENMPC and ENMPC_{aug}. The background colors denote different wind input scenarios: white for REWS, red for Anemometer, light green for LiDaR, and dark green for LiDaR-PF. For a given background color, the left and the right columns show ENMPC and ENMPC_{aug} results, respectively. The black numbers on the top of each bar denote the corresponding relative cumulative values.

The results show that better-providing the controller with more accurate information about the wind disturbance input within the controller leads to increased economic profit for both ENMPC and ENMPC_{aug}. As

expected, the Anemometer scenario, providing only a disturbed point-wise wind measurement, results in the lowest economic profit, while the LiDaR-PF scenario yields the highest economic profit.

610 Furthermore, for all wind input scenarios, the proposed model adaptation results in higher economic profit and reduced pitch and torque travel. The magnitude of the performance improvement varies across the different wind input scenarios. For example, ENMPC_{aug} achieves a 7% higher economic profit in the Anemometer scenario and a 30% increase in the LiDaR scenario, compared to the corresponding ENMPC formulation. It is noteworthy that the economic performance of ENMPC_{aug} in the LiDaR scenario is only slightly worse than that in the LiDaR-PF scenario. This suggests that, for this case study, a perfect wind preview does not significantly pay off, and a simple constant speed estimate is sufficient. However, a more general conclusion can only be drawn by evaluating the two scenarios over a wider range of turbine inflow conditions.

615 4.3.3 Computational performance

An economic controller is real-time feasible if the computational time required to generate the optimal control actions is less than the sample time of the plant. The length of the prediction horizon, along with the nature of the underlying internal model and the optimization problem, directly affects the number of SQP iterations needed for the controller to converge to a solution. A higher number of SQP iterations increases the computational time.

620 Although this work does not focus on optimizing the computational performance of the formulated controllers to ensure real-time feasibility, the impact of the proposed model adaptation on the computational performance of the controllers is assessed.

Figure 9 presents the economic profit and computational time for ENMPC_{aug} LiDaR, with the controller limited to a maximum of three, five, and ten SQP iterations, as reported on the x ~~-axis~~axis. The results are normalized with respect to the ENMPC LiDaR formulation, which uses a maximum of ten SQP iterations. The y ~~-axis~~axis on the left shows the relative economic profit in blue, while the y ~~-axis~~axis on the right displays the relative mean CPU time per controller iteration in orange. The results for ENMPC_{aug} LiDaR are marked with circular markers filled in blue, and the results for ENMPC LiDaR are marked with circular markers filled in green.

630 The simulations were performed on a desktop computer with an Intel i7 processor, a 64-bit operating system, and 8 gigabytes of RAM.

The results clearly show that increasing the number of SQP iterations leads to a higher relative economic profit. For ten SQP iterations, ENMPC_{aug} LiDaR results in a 30% higher economic profit, but it requires more than double the computational effort compared to ENMPC LiDaR. This is because of the additional calculations in the NN part of the model.

635 Interestingly, ENMPC_{aug} LiDaR with only five SQP iterations still achieves a 22% higher economic profit than ENMPC LiDaR with ten SQP iterations, while requiring just 15% more computational effort. This demonstrates that, although the proposed model adaptation increases the CPU time for ENMPC, the improvement in economic performance outweighs the additional computational cost. Moreover, the adapted model requires fewer SQP iterations to generate economically optimal control actions at a smaller actuator usage.

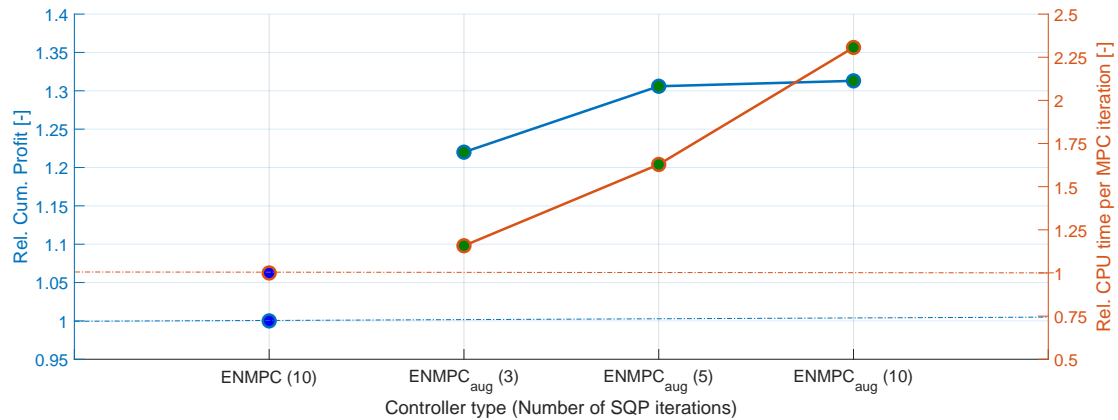


Figure 9. Economic performance and the corresponding CPU ~~computational~~ time requirement for ~~several the~~ ENMPC_{aug} LiDaR ~~formulations~~ formulation utilizing an increasing number of SQP iterations. Performance is normalized with respect to the ENMPC LiDaR formulation utilizing ten SQP iterations.

This effect, combined with the use of high performance computational platforms and further software optimization for speed, 640 may result in real-time feasible economic controllers.

5 Conclusions

MPC uses an approximate representation of the plant to predict the system evolution over a short future horizon. The internal models used by MPC are typically a reduced representation of the plant. The resulting model mismatch affects the feasibility and the optimality of the closed-loop performance. This study presented ~~an a~~ a fatigue-aware adaptive ENMPC for closed-loop 645 control of wind turbines. The ENMPC directly incorporates cyclic fatigue costs using a novel online rainflow counting approach and is able to generate more accurate model predictions through a data-driven adapted model.

The proposed adaptive ENMPC aims to maximize economic profit, which is here computed as the revenue from power generation minus the cost of fatigue damage at the tower base. Revenue is calculated based on the (optionally time-varying) market tariff and the energy supplied to the grid. The cyclic fatigue damage is estimated using online rainflow counting on 650 adapted model predictions, while also accounting for residual cycles. While cycle counting is the only approach to precisely account for fatigue, it also inherently introduces discontinuities in the MPC optimization problem. To address this problem, the PORFC approach is used to externalize fatigue estimation from the MPC optimization. This method estimates time-varying fatigue-related parameters, allowing for a continuous formulation of cyclic fatigue costs that can be numerically optimized within the MPC.

655 ~~Additionally, the ENMPC optimization~~ The ENMPC optimization problem is subject to bound constraints on system states and control variables, ensuring feasible solutions and a stable closed-loop behavior. The ENMPC formulation is further en-

hanced by integrating state and disturbance estimators. These estimators account for measurement uncertainties and provide accurate initial values for the ENMPC.

660 The proposed approach utilizes wind turbine operational or synthetic data with machine learning techniques to predict the mismatch in the system states of plant and ROM. A data-driven model is developed to estimate the error in the states across a range of relevant inflow and control conditions. This process results in an adapted model, where the underlying dynamics are represented by a simple physics-based model combined with data-driven correction terms. The adapted ROM is then used as the internal model within the controller. This process is performed offline, which offers two important advantages. First, it does not introduce additional computational effort during operation, thereby facilitating real-time performance. Second, it results in
665 a certifiable controller, for which safety and performance can be fully assessed offline before deployment in the field. The same is far more difficult – if possible at all – for controllers based on online learning.

The performance of the proposed approach is assessed through a case study using an OpenFAST model of the NREL 5 MW reference wind turbine as plant. This model generates measurement data for the study. The plant model has fifteen degrees of freedom and includes thirty-three system states, while the ROM has only three degrees of freedom and consists of eight
670 system states. The simulation data is generated across a wide range of operational conditions. A feed-forward NN is developed to predict the error in plant and ROM states, and is then used in the adapted model dynamics.

The performance of the proposed model adaptation is initially evaluated in an open-loop setup. In this case, the predictions of the adapted model ROM_{aug} and the baseline ROM are compared with the actual behavior of the plant across a range of operational conditions. The kernel density estimates of the prediction error show that the adapted model performs significantly
675 better than the original model for all eight system states. The performance improvement is further quantified in terms of statistics of the prediction error. The results reveal a reduction in both the mean and standard deviation of errors for all system states, with an approximate 20% reduction in the angular velocity error of the rotor.

Additionally, the effect of dataset size on the open-loop performance of the proposed model adaptation is assessed. Results indicate that even a relatively small subset of training data helps reduce the plant-model mismatch. Performance starts to plateau
680 once 85% of the generated training dataset is used, as additional data samples no longer significantly improve the model. This amount of data is about one order of magnitude smaller than the number of data points typically collected during aeroelastic analyses carried out as part of routine design and certification activities.

To further quantify the impact of model adaptation on the economic control of wind turbines, the closed-loop performance of the proposed economic MPC formulation is assessed by using ROM_{aug} as the internal model of the controller. Five performance
685 indicators are considered: revenue (due to wind power generation), cost (due to tower fatigue damage ~~in fore-aft and side-side directions~~), profit (calculated as the difference of revenue and cost), pitch travel (as a proxy for actuator usage), and torque travel (as a proxy for damage of power electronic converters and drivetrain usage). ~~The optimization problem is solved with the Acados framework using an interior-point solver. The MPC sample time is chosen as 100 milliseconds with a prediction horizon of 2 seconds, where multiple SQP iterations are performed per controller step.~~

690 The performance of ENMPC_{aug} that uses the enhanced model is compared to the ENMPC formulation that uses the baseline ROM as its internal model. Results show that ENMPC_{aug} achieves 9% higher economic profit than ENMPC. This improvement

is attributed to more accurate revenue and cost estimations ~~within ENMPC_{aug}~~, made possible by better predictions of the system states. Additionally, since the future predictions in ENMPC_{aug} are closer to the actual evolution of the plant, the controller requires relatively fewer control actions. This is reflected in a significantly smaller pitch and torque travel compared to the
695 ENMPC formulation.

The benefits of the proposed model adaptation are further assessed across different wind input scenarios. The results show an increased economic profit with improved wind foresight, for both ENMPC_{aug} and ENMPC. Moreover, the model adaptation leads to higher economic profit – up to 30% in the LiDaR scenario – and reduced pitch and torque travel for all wind input scenarios.

700 Although this study did not focus on optimizing the computational performance of the controllers for real-time feasibility, the impact of model adaptation on computational performance was also evaluated. The results show that increasing the number of SQP iterations leads to higher economic profit but also increases computational expenses. Additionally, for the same number of SQP iterations, ENMPC_{aug} is more computationally expensive than ENMPC due to the extra computational cost due to NN evaluations. However, when considering LiDaR wind estimates, ENMPC_{aug} achieves a 22% higher economic profit while
705 requiring only 15% more computational effort compared to ENMPC. Therefore, the proposed model adaptation, combined with high-performance computing platforms and additional software optimization (not considered here), could enable real-time feasible economic controllers.

The accuracy of offline ~~data-driven model corrections heavily depends~~ data-driven model corrections depends strongly on the quality of ~~its~~ the training process, which requires a comprehensive dataset ~~characterizing that characterizes~~ the range of
710 operational conditions ~~of experienced by~~ a wind turbine. In ~~reality, the practice,~~ wind turbine OEMs typically have validated ~~high-fidelity turbine models from the~~ high-fidelity turbine models developed during design and prototyping phases. ~~These, and these~~ models can be used to represent ~~the wind~~ turbine behavior and generate the ~~dataset. Moreover, OEMs sometimes also required dataset. Moreover, OEMs often~~ have access to ~~high-resolution data from on-board sensors of operational turbines that can also high-resolution measurements from on-board sensors of operating turbines, which can further~~ contribute to the
715 ~~required dataset. A dataset. The~~ generalized usability of the adapted model ~~relies depends~~ on how similar ~~the~~ turbine behavior is ~~from one installation site to another, a problem that was not investigated here~~ across different installation sites, an aspect that has not been investigated in this work.

Future work should focus on developing a more comprehensive economic objective that accounts for ~~the fatigue damage of~~ fatigue damage affecting additional turbine components, such as the bearings and ~~the~~ drivetrain, while also incorporating a more
720 realistic profit ~~evaluation model. Currently, model. This would require applying the PORFC formulation to other fatigue-critical components of the turbine and integrating it within ENMPC as either an objective function or a constraint. The assessment can be extended to new scenarios that consider more dynamic variations of exogenous inputs, such as market prices over longer evaluation periods. At present,~~ the profit formulation ~~overlooks the impact neglects the influence~~ of fatigue on component reliability and O&M costs, and ~~only considers it considers only~~ tower fatigue damage. ~~Additionally, the physics-based internal~~
725 ~~model dynamics~~ In addition, the physics-based internal model can be expanded to ~~better~~ capture dependencies on ~~other a wider~~

set of system states. ~~Furthermore, the model can be enhanced to include~~ The model can also be improved by introducing online tuning of ~~the model parameters~~, model parameters in addition to the offline augmentation used in this study.

Appendix A: Nomenclature and abbreviations

	DLC	Design load case
730	DOF	Degree of freedom
	ENMPC	Economic nonlinear model predictive control
	ENMPC _{aug}	Economic nonlinear model predictive control having ROM _{aug} as the controller-internal model
	FA	Fore-aft
	LiDaR	Light detection and ranging
735	MHE	Moving horizon estimator
	MPC	Model predictive control
	NFWS	Nacelle filtered wind speed
	NLP	Nonlinear program
	NN	Neural network
740	O&M	Operation and maintenance
	ODE	Ordinary differential equation
	OEM	Original equipment manufacturer
	PDE	Probability density estimate
	PF	Perfect foresight
745	PORFC	Parametric online rainflow counting
	QP	Quadratic program
	RAWS	Rotor averaged wind speed
	REWS	Rotor effective wind speed
	RMSE	Root mean squared error
750	ROM	Reduced order model
	ROM _{aug}	Augmented reduced order model
	SQP	Sequential quadratic program
	SS	Side-side
	STD	Standard deviation
755		
	ξ	Slack variable
	\bar{v}	Noise variable

	ω	Rotor speed
760	β_b	Blade pitch angle
	β_c	Commanded blade pitch angle
	σ	Stress at tower base
	η	Power conversion efficiency of the drivetrain
765		
	F	Set of dynamic equations of a model
	F_{NN}	Function mapping of the NN
	$\Delta\mathbf{F}$	Set of dynamic equations of the correction model
	F_T	Aerodynamic thrust force
770	J	Optimization objective
	J_r	Moment of inertia of the rotor
	N_u	Number of intervals in the controller prediction horizon
	P	Electrical power output of the turbine
775	$R_m Q_g$	Ultimate tensile strength of the material <u>Aerodynamic torque</u>
	$T_g Q_g$	Generator torque
	$T_{gc} Q_{gc}$	Commanded generator torque
	$T_Q R_m$	Aerodynamic torque <u>Ultimate tensile strength of the material</u>
	T_{ctrl}	Sample time of the internal model and the controller
	$T_{horizon}$	Prediction horizon of the controller
780	$T_{horizon,est}$	Prediction horizon of the state estimator
	T_{sim}	Sample time of the plant
	V_w	Wind speed
	W	Weight
785		
	a_m	Initial capital cost of the machine
	b	Bias
	c	Cycle
	d	Disturbance variable
790	$d_{T_{FA}}$	Tower-top deflection in fore-aft direction
	$d_{T_{SS}}$	Tower-top deflection in side-side direction
	e	Error in state
	f^{act}	Activation function

	i	Time instant
795	m	Time-varying PORFC parameter: mean
	p	Free model parameter
	t	Time
	Δt	Difference in time between current and next instants <u>Time step</u>
	u	Control variable
800	w	Time-varying PORFC parameter: weight
	x	State variable
	x_{NN}	Input feature of the NN
	y_{NN}	Output feature of the NN
805		
	\mathbb{b}_{1-2}	Model parameters for blade dynamics
	\mathbb{f}_{1-3}	Model parameters for tower fore-aft dynamics
	\mathbb{g}_1	Model parameters for generator dynamics
	\mathbb{m}	Fatigue exponent derived from material properties
810	\mathbb{s}_{1-4}	Model parameters for tower side-side dynamics
	\mathbb{t}_1	<u>Model parameters for estimating tower-base stresses using tower-top deflections</u>
	\square_{aug}	Augmented
815	\square_{est}	Estimation
	\square_{gen}	Generation
	\square_{meas}	Measurement
	\square_{prev}	Previous
	\square_{sim}	Simulation
820		

Code and data availability. A Python script to extract PORFC parameters for a given stress time series can be accessed on Zenodo at <https://doi.org/10.5281/zenodo.15530467> (Anand and Bottasso, 2025). The data for figures 3-9 can also be retrieved in Python pickle format from the same Zenodo repository.

825 *Author contributions.* AA and CLB developed the adaptive economic MPC formulation. AA implemented the model correction, the adaptive economic controller, carried out the simulations, and generated results. All authors contributed to the interpretation of the results. CLB supervised the overall research. AA and CLB prepared the manuscript. All authors provided valuable input to this research work through discussions, feedback, and improvement of the manuscript.

Competing interests. At least one of the (co-)authors is a member of the editorial board of *Wind Energy Science*.

830 *Financial support.* This work has also been supported by the e-TWINS project (FKZ: 03EI6020), which received funding from the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Acknowledgements. The authors would like to acknowledge Stefan Loew for his valuable inputs to the overall work, and Filippo Campagnolo for his support in the implementation of different wind inputs.

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