Reply on RC1 – PDF Format

- Detailed Comment 1:

  Figure 8 reports the output time series for the high-fidelity model and for the surrogate model. It can be seen on the figure that at t=0 h the charge power is positive and the discharge power is negative. One would expect the discharge power to be zero. Furthermore, the power output of the HPP is negative between t=2 and 4 h, assuming that the HPP is able to charge from the grid. These two points raise questions on the ability of the surrogate model to represent a valid storage model. Please expand the discussion of Figure 8 to include these considerations.

  Answer 1:
  The purpose of showing the time series in Figure 8 (now Figure 6) is to demonstrate the hourly performance of the surrogate. While the trends and fluctuations within the HPP output are well captured, the same cannot be said for the other time series. This highlights the ability of the surrogate to represent the HPP operation as a whole, but its inability to describe the hourly operation of each technology individually with high accuracy. These issues arise from the nature of the regressor; the FNN cannot inherently capture the physical constraints that multiple equations would typically enforce. Specifically, the FNN lacks explicit equations to govern its outputs. However, for this study, focusing primarily on the power output of the HPP is sufficient, as this is the only variable required in revenue calculation and subsequent profitability index evaluation.

  Changes in paper:
  Additional discussion is added in Section 6 to elaborate on that. l. 529-537

- Detailed Comment 2:

  The story line of the paper focuses on the field of system integration of renewable energy and hybrid power plants. In order to fit better in the scope of Wind Energy Science, consider highlighting the relevance of this study for the field of wind energy in the introduction, discussion and conclusion of the manuscript.

  Answer:
  Additional text was added at the start of the introduction and discussion and at the end of the conclusion to highlight the study's relevance.

- Detailed Comment 3: Motivation and research question:

  3.1:
  l. 37: “ The importance of a realistic EMS …” : it is unclear from the literature review what is the difference between a high- and low-fidelity model for the EMS. The manuscript provides an overview of different high-fidelity models used in the field but does not describe the low-fidelity ones. The following reference may be of interest in this context:
  Stanley, A. P. J., & King, J. (2022). Optimizing the physical design and layout of a resilient wind, solar, and storage hybrid power plant. Applied Energy, 317, 119139.
  https://doi.org/10.1016/j.apenergy.2022.119139

  Answer:
  To explain the differences between the High-Fidelity (HF) and LF (EMS), additional literature was added within the introduction (l. 59-76), and a new table was added: Table 1. Comparison of HF and LF EMS Models.

3.2:

Table 1 reports that 1000 "iterations [are] required to find [a] refined solution". Please put this number in context with the literature. Is it characteristic of HPP sizing problems to require a large number of iterations to converge?

Answer:

The short answer is that from previous work that authors are familiar with (Leon et al., 2024), we need to evaluate hundreds of different sizes to reach an optimal sizing.

Changes in Paper:

The previous Table 1 is now removed and replaced with another table, Table 1. Comparison of HF and LF EMS Models. Instead, we provide more details on the sizing problem in the introduction l. 76-102.

3.3:

l. 59: "HPP sizing optimization often relies on a simplified EMS representation": the introduction of the paper does not describe the problems associated with using a simplified or low-fidelity EMS model. As such, it is unclear why one would prefer a high-fidelity model in a context where computational cost is a problem. Please describe explicitly and quantitatively why a high-fidelity model is superior to a low-fidelity one.

Answer:

Although no studies directly compare HF and LF EMS models, it is evident that LF EMS models sacrifice accuracy due to simplifications in areas such as component modeling, market bidding strategies, and operational constraints. These simplifications can result in inaccurate power schedules, leading to revenue projections that may misrepresent the business case for a given HPP sizing. Quantifying the extent of deviation between low- and high-fidelity EMS models is beyond the scope of this paper; however, we are currently researching this topic.

Nonetheless, Zhu et al. 2024 examined the accuracy of total profits across three HF EMS models, demonstrating that even among HF models, certain simplifications commonly found in LF models—such as relying on deterministic forecasts—can lead to revenue discrepancies of up to 7.6% when compared to the best-performing model (refer to Table 3 of the paper).

Although this provides some insight into the potential impact of LF EMS simplifications, a comprehensive study comparing HF and LF EMS models for HPPs is currently being conducted by colleagues in our research group.

Changes in paper:

A paragraph (l. 103-109) was added to explain the current state of the research on comparing HF and LF models:

3.4:

The list of major contributions is a good addition to the introduction. Consider writing explicitly the research question for the study.

Answer:

The research question was added before the list of contributions. l.166-167

3.5:

l. 100-101: “Integration of the developed surrogate within a framework to evaluate the profitability of an HPP sizing with high accuracy.”: this statement is convoluted. Consider combining it with the previous one, e.g.: “Assessment of the surrogate model’s ability to calculate … time series and profitability of the HPP …”

Answer:
As the three points are distinct, we would like to keep them separate. The wording was modified to make it more straightforward.

Changes in Papers:
The second and third points were reformulated (l.171-174).

- Detailed Comment 4: Methodology

<u>4.1:</u>
Two of which use a multivariate linear regression to establish a baseline and two others are based on Neural networks (NNs)”: please put in context the choice of surrogate models in the introduction. What are the strengths and weaknesses of these models? Have they been applied to models similar to HPP dispatch strategies? Can one expect them to perform well for this type of problem? Are there other surrogate models one could consider for HPP dispatch strategies?

Answer:
In the revised introduction, we have discussed data-driven surrogate models, showcasing successful applications of both regression models—ranging from linear to more complex Neural Networks (NNs). These models are often applied to solve problems involving partial differential equations where a large number of parameterized instances must be evaluated. In such cases, thousands of degrees of freedom are typically required to achieve accurate solutions, leading to significant computational demands, especially in scenarios requiring real-time simulations.
This challenge is similar to our current problem, where the high-fidelity EMS model must be solved across hundreds of HPP sizing configurations. For each sizing, the EMS model operates at an order of magnitude involving hundreds of thousands of degrees of freedom, creating a substantial computational burden. Given that the use of surrogate models for EMS in grid-connected HPPs is largely unexplored in the literature, we examined a range of potential surrogate models. Our exploration includes simple approaches, such as linear regression, and more sophisticated models, like feedforward neural networks (FNNs), initially chosen based on their adaptability to our specific problem.
The linear regression model serves a dual purpose: firstly, to assess if a linear approximation can capture the essential dynamics of our problem, and secondly, to provide a baseline against which we can measure the improvement in accuracy and computational cost when using more complex surrogate models.

Changes in paper:
Additional text was added: l.120-149

<u>4.2:</u>
In the first part of section 5, the four surrogate models are compared. However, only one model is used for the rest of the results section. This leads to a lengthy result section, where the high impact results are more difficult to identify. Consider either (i) focusing on the best surrogate model in the entirety of section 5 and moving the comparison between linear and NN models in an appendix; or (ii) compare all four models for all relevant metrics. This second approach would help the reader have insight on the trade-off between accuracy and computational time.

Answer:
Thank you for the suggestion. We decided to go with the first option, and changes were made in Section 5 accordingly.

Changes in paper:
Figure 6 is now Figure A1, and Table 10 is now Table A1.
Moved previously numbered Figure 6 (now Figure A1) and Table 10 (now Table A1) to Appendix A: Surrogate Models Comparison and the corresponding text.
Only figures related to the best-performing surrogate models (S4) were kept in Section 5.

<u>4.3:</u>
The surrogate models are compared to each other, with the high-fidelity EMS as a reference. However, the results would be significantly strengthened if the comparison were to include a low-fidelity model. For example, if the RMSE for the low-fidelity EMS was 10 times higher than the linear and NN models (Figure 6), this would provide an excellent motivation for the use of a surrogate.

Answer:
Thank you for the suggestion. While I agree that including a comparison with a low-fidelity EMS would provide additional context and further strengthen the results, the focus of this study is specifically on the use of surrogate models as a computationally efficient alternative to high-fidelity EMS. As Zhu et al. (2024) demonstrated, even minor simplifications typical of low-fidelity EMS can lead to significant revenue discrepancies, with observed differences reaching up to 7.6% compared to the most accurate high-fidelity model. This suggests that the discrepancy would be even greater with a low-fidelity EMS.

Additionally, our colleagues' ongoing research explicitly addresses the comparison between high- and low-fidelity EMS models. While the insights from that work would be valuable here, incorporating it is beyond the current scope of this paper. Instead, this study focuses on evaluating the accuracy and computational benefits of surrogate models relative to high-fidelity EMS, as this comparison more directly aligns with the primary goals of the research.

<u>4.4:</u>
l. 208: “applied for the 2nd and 4th surrogate models”: consider introducing a name for each surrogate, instead of referring to their number in Table 5. The names should match the labels of the figures in the results section.

Answer:
The names of the surrogates have been changed to S1-S4, please refer to Table 5 for the definition of each model. Other changes in the text and figures have been applied.

<u>4.5:</u>
l. 407: “as the linear model cannot capture the inherent non-linearities of the high-fidelity model.”: why has a linear model been chosen? This statement suggests that the choice of methodology is not appropriate for the study.

Answer:
Thank you for pointing that out. I will revise the statement to clarify this aspect.

In addition to the reasons mentioned earlier for selecting the linear regression model, we recognize that the EMS exhibits some non-linear behaviors. However, we also suspect these non-linearities are relatively mild, as most of the system's constraints are linear. Therefore, we included the linear regression model to evaluate its effectiveness in approximating the high-fidelity model. This approach allows us to establish a baseline and assess the extent to which a simple model can capture the EMS's behavior before moving on to more complex surrogate models.

Changes in paper:
Sentence added in l.437-439

- Detailed Comment 5: Literature review

5.1:
On the topic of energy markets and subsidies for renewable energy, consider referring to the following report: European University Institute: Robert Schuman Centre for Advanced Studies, Kitzing, L., Held, A., Gephart, M., Wagner, F., Anatolitis, V., & Klessmann, C. (2024). Contracts-for-difference to support renewable energy technologies : considerations for design and implementation, European University Institute. https://data.europa.eu/doi/10.2870/379508

Answer:
Thank you for the recommendation. The paper is now cited in the introduction, and additional context was added since the writing of this report, e.g., the Agreement of May 2024. l.20-24

5.2:
The literature review would be strengthened by citing literature related to machine learning and data-driven methods. An overview of methods for modelling time-series would be a good addition to the paper.

Answer:
Additional literature on these topics has been added. l.120-149

5.3:
Consider including a short description of the advances done on hybrid power systems (e.g. for micro-grids). This would help contextualize better the paper since the problem of storage sizing and dispatch strategy has been addressed in this field before, even though not in relation to electricity markets.

Answer:
Additional context was added in l.53-58.

5.4:
The literature review could be complemented by citing articles related to the field of bidding strategies. For example, the works by Pierre Pinson or Kenneth Bruninx may be of interest:
Ding, H., Pinson, P., Hu, Z., & Song, Y. (2016). Integrated Bidding and Operating Strategies for Wind-Storage Systems. IEEE Transactions on Sustainable Energy, 7(1), 163–172. https://doi.org/10.1109/TSTE.2015.2472576
Toubeau, J.-F., Bottieau, J., De Greeve, Z., Vallee, F., & Bruninx, K. (2021). Data-Driven Scheduling of Energy Storage in Day-Ahead Energy and Reserve Markets With Probabilistic Guarantees on Real-Time Delivery. IEEE Transactions on Power Systems, 36(4), 2815–2828. https://doi.org/10.1109/TPWRS.2020.3046710

Answer:

Thank you for the suggestion. These papers have been cited.

- Detailed Comment 6: Structure of the paper

6.1:
The last sentence of the first paragraph states that BESS are valuable to establish robust business cases. Then, the second paragraph discuss the definition of HPPs. In this case, the link between the two paragraph is not clear. Instead, consider introducing HPP in the first paragraph, and narrowing the focus of the study on HPP with storage systems.

Answer:
Both paragraphs were modified according to the comment: l. 27-36

6.2:
l. 68- 71: “To evaluate the value of HPP, …”: this paragraph discussing performance metrics for HPPs does not seem relevant in the introduction. Consider moving it in a later section describing the profitability index.

Answer:
Agreed. This sentence was integrated in Section 3 (l. 349-353), where financial metrics are discussed.

6.3
l. 118-125: “In electricity trading …”: the description of the spot and balancing market does not help describing the methodology of the study. Consider moving this paragraph to the introduction.

Answer:
The paragraph was shortened and integrated in the introduction: l. 41-52.

6.4
Consider restructuring section 2 and 3 into one section describing the metrics relevant to HPPs (including the description of the relevant time series, the EMS and the profitability index) and one section describing the surrogate models.

Answer:
After discussing this with most co-authors, the majority wished to keep the current structure.

6.5
l. 185-186 “Details on the normalization process appear later on” and l. 189 “The specific use of this method is detailed in this section”: instead of referring the reader to a later part of the paper, consider restructuring the subsection.
Consider shortening the description of the normalization steps (l.194-205) and instead state that scaling is used for all time series.

Answer:
The subsection was slightly restructured, and the description was shortened as suggested.

6.6
l. 213-218: the description of the shapes of the matrices does not seem relevant for the study. Consider removing the associated sentences or moving them to an appendix.

Answer
These descriptions were removed.

6.7
Please restructure and shorten section 2.2.3. The text mixes general statements about training neural networks, mentions of the steps of the methodology (l. 235 and l. 255 "the best-performing model … is selected") and descriptions of the training methodology. This makes the subsection difficult to follow.

Answer:
It seems there is some confusion. The selection of the best-performing model is part of the training process. This does not refer to selecting the best-performing model among the four types of surrogates, S1-S4; instead, this refers to one surrogate type, e.g., S3 or S4. In the tunning process, several hundred models are evaluated for a given type of surrogate (S3 or S4). These hundreds of models differ in the choice of hyperparameters. Among these, the best performing model is selected and further trained "till convergence." The training method described needs to be applied individually for surrogate types S3 and S4.
A workflow example for model S3 would be as follows:
Apply normalization to inputs and output --> define FNN architecture and hyperparameter search space --> Proceed with tuning --> Result: hundreds of FNN trained --> Get the most accurate FNN based on the defined loss function (MSE) --> Further train that model till convergence --> Result: model S3.

The section was modified and shortened to make it more straightforward.

Please let us know if we have misunderstood your comment.

6.8
Consider moving the description of the cost model to an appendix (l. 322-344)."

Answer:
The description of the cost model has now been moved to Appendix C: Cost Model. Moreover, the data related to the cost model has been moved; previously, Table 9, now Table D2, has been moved to Appendix D: Data Supplement.

- Detailed Comment 7: Clarity and conciseness

7.1
l. 25 "power plants that combine several technologies": please precise the type of technology. Consider using the terms "electricity generation and storage technologies".

Answer:
The wording was changed to "combine several generation technologies, including wind turbines, and possibly energy storage": l.30-31

7.2
l. 32-35: "As HPPs transition to market-driven revenue models… throughout the power plant's lifetime": the start of this paragraph is vague. What are the "new possibilities and challenges" mentioned? What does the expression "navigate energy markets" mean in the context of the study? What are the characteristics of a "detailed operational strategies"?

Answer:
A paragraph was added before explaining the meaning of market-driven models, i.e., CFD. The text was further modified to explain the opportunities, challenges, and detailed operational strategies. l. 37-52

7.3
l. 35 “Energy Management System”: please define the term, and highlight the difference between other types of “control” in the context of HPP. Consider stating the difference between EMS and adjacent terms such as bidding or dispatch strategies.

Answer:
A first definition of the EMS is given in the introduction l. 38-41. A more detailed definition is now given in Section 2.1 to clarify which EMS is used in this article. l. 191-200.

7.4
l. 95: “Development of a fast and precise surrogate”: the term “accurate” seems more pertinent in this context.

Answer:
The term was modified.

7.5
l. 98 “Assessment of the surrogate’s ability to predict hourly operational time series”: consider using the verb “compute”, “calculate”, “model” or “estimate” instead of “predict”, since the latter implies a focus on future (and unknown) data.

Answer:
Thank you for the suggestion. Similar changes were applied to the paper.

7.6
Please precise what the term “surrogate model” means in the context of the study. By itself, “surrogate” implies a simplified or approximation model, and does not refer to data-driven or machine learning methods specifically.

Answer:
Additional literature on data-driven surrogate models was added to the introduction to give context to the developed surrogate models. Additionally, the paragraph of section 2.2 gives a detailed definition of the term in this study.

7.7
l. 404: “This RMSE provides a holistic measure of the model’s accuracy”: why is the term “holistic” used here? Consider rephrasing.

Answer:
The sentence was changed to: "Since this RMSE is calculated across all output time series, it provides a broad assessment of the model's accuracy, without specific insights into each individual series." l.322-323.

7.8

l. 413: “Table 10 contrasts the time required to execute the workflow for each surrogate model” Consider rephrasing this sentence.

Answer:
The sentence was changed to: "Table A1 compares the time needed to execute the methodology for each surrogate model." l.592.

7.9
l. 426: “Figure 8 shows the difference between the surrogate’s prediction and the ideal behavior”: what does “ideal behavior” mean here? Consider rephrasing.

Answer:
The sentence was changed to: "Figure 6 shows the difference between the surrogate's approximation and the HF EMS' outputs" l. 458.

7.10
l. 537 “the synergistic use of SVD and FFN”: what does “synergistic” mean in the context of the study? Consider rephrasing.

Answer:
Changed to: "A key innovation of our study is the combined use of SVD and FNN, which represent a novel approach in this field." l. 576-577.

7.11
l. 542: “a mere 25 seconds” and “remarkable accuracy”: Please avoid subjective terminology and use neutral language instead."

Answer:
Removed these terminologies

- Detailed Comment 8: Figures

8.1:
What is the information conveyed by Figure 4? Consider removing it.

Answer:
The Figure is removed.

8.2:
Figure 5.b. : this representation of the wind distribution is unusual. A more standard representation as the probability distribution function would be more meaningful for the reader.

Answer:
The previously numbered Figure 5 is now Figure 4.
Thank you for the feedback. Although the violin plot representation may be less conventional, it was chosen for its ability to convey detailed insights into the distribution of wind power across multiple locations within a single, compact visualization. Overlaid PDF plots were considered; however, they tended to appear cluttered, making it difficult for readers to extract meaningful information. Separate PDF plots for each location were also examined, but they would have required significantly more space. While a CDF plot was another option, its interpretation is less intuitive than the violin plot, especially for readers less familiar with cumulative distributions. To

enhance clarity, we have included additional text (l. 413-426) explaining how to interpret the violin plot, which should aid in understanding its unique presentation.

8.3:
"Please follow the journal guidelines for the captions: https://www.wind-energy-science.net/submission.html#figurestables "

Answer:
Figures were changed to comply with the guidelines.

8.4:
Consider using intelligible notation in the legend and labels when possible, instead of introducing the notation in the caption. For example, the labels of Figure 7 do not correspond to previously introduced notation.

Answer:
Note that Figure 7 is now Figure 5.
The notations are now introduced in the texts and then used in the figures. The notations are now consistent among all figures, tables, and text.

8.5:
Figure 6,7 and 10: including the equation for the RMSE in the label seems unnecessary since the notation and equations is introduced in the main text.

Answer:
Figures were modified.
Note that Figures 6, 7, and 10 are now A1, 5, and 8.

8.6:
Figure 8: Please indicate the unit on the figure labels.

Answer:
The units are now included.

8.7:
Figure 9: it is unclear why two figures are relevant here. Consider removing Figure 9 (a).

Answer:
Note that Figure 9 is now Figure 7.
Figure 7(a) is shown because it is hard to visualize the extent of the scatter from the PDF plot shown in Figure 7(b). This scatter helps to understand the deviations from the HF EMS, as shown in Figure 6 (previously Figure 8).

8.8:
l. 443: “The mean (μ) being close to zero suggests…”: Note that Figure 9(b) indicates that the mean is equal to zero.

Answer:
Text changed to avoid confusion: l. 475.

8.7:

Section 2.1.: a figure illustrating the EMS would be relevant to support its description in the text. For example, Figure 1 could be extended to describe the time schedule for bidding and dispatch decisions.

Answer:

Figure 1 was modified. Additional information was added to the bidding process. Additional text was added to explain further the bidding process of the EMS (l. 207-217). For clarity, throughout the article, the use of the acronym "EMS" was slightly changed: when applicable, "EMS" was modified to "SM optimization", referring to the bidding process happening at the day-ahead stage. The acronym "PMS" was removed entirely and replaced by Real-Time (RT) dispatch. The HF EMS combines both SM optimization and RT dispatch.

Detailed Comment 9: Equations

9.1:

For the presentation of the equations in the manuscript, consider introducing the relevant metrics and their notations before the equation.

Consider adding a paragraph or a subsection to introduce the notation used in the paper, since there is a wide variety of symbols, subscripts and superscripts in the manuscript.

l. 268-271: please introduce notation in a paragraph and not as a list. This comment applies to subsequent equations as well.

Answer:

Thank you for the feedback. The notations are now introduced in a paragraph before the equations.

9.2:

Equations 1 to 3 are not equations since they don’t include an equal sign. Consider giving each scalar parameters a name, a symbol and describe their meaning.

Answer:

Indeed, apologies for the oversight. They are now included in the paragraph instead.

9.3:

The notations “SM” (l.211) and “\lambda” (Eq. 10) are used to describe the price of electricity. Please use a consistent notation throughout the paper.

Answer:

Thank you for pointing it out, the notation SM_t is now used throughout the paper.

9.4:

"Equation 8: consider introducing a specific symbol for the RMSE instead of using the abbreviation."

Answer:

The notation of RMSE was changed to ε_{RMS} and NRSME to $\varepsilon_{NRMS.}$

Detailed comment 10:

<u>10.1:</u>
Please describe in the abstract that the study was conducted for participation on the day-ahead market and for Denmark.
Please include in the abstract the assumption of perfect forecast.

Answer:
The additional information was added.

<u>10.3:</u>
"Sizing of Hybrid Power Plants (HPPs), which include wind power plants and battery energy systems, is essential to capture tradeoffs among various technology mixes": please be more specific.

Answer:
The tradeoff mentioned is an economic tradeoff, that could lead to over- or under-sizing a HPP.

Changes in paper:
The reformulated first sentence of the abstract.

<u>10.4</u>:
l. 4 "model the operation of a battery when participating in any market": please be more specific about the market mentioned here.

Answer 10.4:
The term was changed to electricity market. Later in the abstract, we mention that the study focuses on the day-ahead market.

<u>10.5</u>:
l. 5: "Traditional EMS" : what does "Traditional" mean here? Consider rephrasing.

Answer:
Based on context, we have Replaced "Traditional EMS" with either High-fidelity EMS or LF EMS.

- Minor comments

All minor comments have been addressed, and changes have been made accordingly.

Concerning the comment:
"Be aware that Wind Energy Science guidelines state that grey-literature may only be cited if there are no alternatives. The international hybrid power plant conference is grey literature, due to its lack of peer-review: "Das, K., Hansen, A. D., Koivisto, M., and Sørensen, P. E.: Enhanced features of wind-based hybrid power plants, Proceedings of the 4th International Hybrid Power Systems Workshop, 2019."
"

We have contacted the Workshop organizers and received the following reply:
"
That's partly correct, we only review the abstracts, in the short time between paper deadline and the workshop (about 4-6 weeks) we cannot completely review 180 papers. But those papers which are published in the IEEE Explorer should not be considered gray-literature as IEEE is running them

though their quality check... also, in the last few years we published the proceedings in a digital data base, see https://digital-library.theiet.org/content/conferences/cp847, so if you mentioned the ISBN Number in the reference, it should qualify as a reference.

However, we only started with the digital data base in 2021, but all older proceedings also have an ISBN number and the proceedings have been submitted to a number of University library in Europe, so papers could be found by interesting parties. The relevant reference for the 2019 workshop is:

Proceedings 18th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Plants
Dublin, Ireland, 15-16 October 2019
ISBN: 978-3-9820080-5-9
"