# Information how to read the document

- RC: Referee Comment
  - Pages and lines in the author comments refer to the manuscript submitted before the revision process, as we did not want to change author comments here.
- AR: Authors Response
  - To avoid confusion, we have removed the line references in our responses that we mentioned in our author comments, as these referred to the unmarked revised manuscript, and we now include them in the author changes.
- AC: Authors Changes
  - Parts indicated in blue were added, parts indicated red and which are crossed out were deleted – all lines and page numbers refer to the lines in the marked-up manuscript for easy trackability.

# RC1

| | |
|---|---|
| **RC** | **The presentation should be improved. Several abbreviations are used before being clearly defined. For example, "RV" and "AP" should be introduced with their full names when they first appear.** |
| **AR** | Both "RV" and "AP" are now fully introduced at the first time they are mentioned. Additionally, "MIL" was introduced twice. Once on page 4 and again on page 15. The latter introduction was deleted. |
| **AC** | - |
| | *Page 4, line 100:*<br>First we establish a conservative baseline design. Following the approach of Hofrichter et al. (2023), ~~the design phase to optimize~~ the rated electrolyzer power and BESS capacity are sized to maximize the annual profit (AP) based on a fixed, rule-based ~~employs an~~ operation strategy that defines power flows for all design components. Crucially, this initial design phase is coupled with a detailed degradation evaluation. In a second step, a mixed-integer linear (MIL) operation optimization is applied to this designed system…<br><br>*Page 6, line 143:*<br>…and a reference value (RV) describing the average expected electricity price achieved over the lifetime of the WF.<br><br>*Page 15, line 395:*<br>This subsection introduces the ~~mixed-integer linear (~~MIL~~)~~ operation optimization… |

| | |
|---|---|
| **RC** | **There is a cross-reference error on page 6, lines 148–149. The text contains the unresolved reference: "Fehler! Verweisquelle konnte nicht gefunden werden. (Lagarias et al. 1998)." This should be corrected.** |
| **AR** | The reference is now given correctly. |
| **AC** | Page 6, line 162 |
| | …, which ~~that~~ is further described in Sect. **Fehler! Verweisquelle konnte nicht gefunden werden.**. |

| | |
|---|---|
| **RC** | **The terminology should be made consistent. The manuscript uses both "HRES" and "HWF" to describe the co-located wind farm, electrolyzer, and battery system. This may confuse readers. In addition, this type of generation system is commonly referred to as a hybrid power plant ( HPP). The authors are encouraged to check the definition of HPP used by IEA TCP Wind Task 50 and align the terminology accordingly.** |
| **AR** | According to IEA TCP Wind Task 50 the latest publication is the annual report from 2024. Figure 1 in this annual report shows a decision tree for determining the type of hybrid energy system being used, created by Work Package 1. According to this decision tree our described co-located wind farm, electrolyzer, and battery system is a grid-connected, unidirectional, multi-commodity hybrid power plant (HPP). Both abbreviation HRES and HWF are therefore replaced with HPP. |
| **AC** | - |
| | *Page 2, line 49:*<br>One way to counter these problems are ~~hybrid renewable energy systems (HRES)~~ hybrid power plants (HPP)… (*In the following sentences HRES and HWF were replaced by HPP. In total it has been 36* |

| | |
|---|---|
| | *replacements in the whole manuscript. For the sake of clarity, we have omitted a list of all these changes here.)*<br><br>*Page 3, line 95:*<br>~~Since all components will be placed close to an already existing WF we will further call the considered HPP a hybrid wind farm (HWF).~~ |

| | |
|---|---|
| **RC** | **The operational strategy in Figure 2 should be clarified. The strategy appears to be rule-based, but the current figure is difficult to follow. The authors are encouraged to present the operational logic as a flowchart, which would make the decision process for power allocation among the wind farm, electrolyzer, BESS, and grid more transparent.** |
| **AR** | We appreciate the reviewer's suggestion regarding the presentation of the operational logic. As illustrated in Figure 2, the system's dispatch logic is governed by the interaction between wind farm power output and the battery energy storage systems state of charge, resulting in nine distinct operational states. Each state involves specific power allocation setpoints for the electrolyzer, the grid interface, and the battery energy storage system.<br><br>Given the multi-variable nature of these transitions, mapping all nine configurations and their respective decision branches into a single flowchart would lead to an overly complex and potentially fragmented diagram. We believe that the current consolidated representation provides a more concise and readable overview of the interdependent power flows. To improve clarity, we have refined the caption of Figure 2 to ensure the decision logic is more intuitive for the reader. |
| **AC** | Page 12, Figure 2 |
| | **Figure 1:** ~~**Overview of power flows for a timestep in the assumed operation strategy.**~~<br><br>**Figure 2: Power flows of HPP components for the determined operation strategy for a timestep depending on the relative WF power output (top row) and the BESS state of charge (left column).** |

| | |
|---|---|
| **RC** | **Battery degradation should be considered or discussed in more depth. The BESS is central to the conclusions: it reduces electrolyzer degradation and increases annual profit, while only slightly increasing LCOH. However, BESS degradation and replacement are neglected, although the manuscript acknowledges that cycling degradation could affect the optimal BESS capacity. The authors should either include battery degradation in the model or provide a more detailed discussion of how battery degradation may influence the main conclusions.** |
| **AR** | We agree that the BESS degradation is a central factor given its role in the system's economic performance. To address this, we have significantly reduced the assumed BESS lifetime from 30 years to 10 years within the design method. This change ensures that BESS replacement is now more frequent which results in higher levelized cost of hydrogen (LCOH) and annual profits.<br><br>Within the MIL operation optimization, we have introduced cycle-based degradation costs into the objective function. These costs are derived by linearizing the replacement costs over the expected total energy throughput. This ensures that the BESS is only dispatched when the economic benefit exceeds the costs of its own wear. We assume the replacement costs to be the initial investment costs (CAPEX) and that the BESS reaches its end of life after 8000 cycles.<br><br>These updates on BESS degradation provide a more detailed economic assessment. While the system's optimal battery capacity decreases, the fundamental conclusion remains unchanged: the BESS remains a vital component for the economic viability of the plant, primarily due to its protective effect on the high-value electrolyzer asset. Specifically, the MILP operation optimization reveals that the BESS undergoes only about one cycle per day, extending its expected service life to around 22 years. This demonstrates that the 10-year lifetime baseline assumed in the design method is highly conservative. |
| **AC** | |
| | *Page 15, line 406:*<br>Additionally, for the BESS, linear cycle-based degradation costs are added to t~~T~~he objective function ~~within the MIL optimization~~ that is defined as<br>$\max(OAP) = \max(\sum_{t=0}^{T}\left(SE(t)\cdot p_{\mathrm{elec}}(t) + SH(t)\cdot p_{\mathrm{hy}}(t) - WSC(t)\right) - DegC_{\mathrm{El}} - DegC_{\mathrm{BESS}})$, |

*Page 16, line 414:*

$\mathrm{DegC}_{\mathrm{BESS}}$ denotes the degradation costs of the BESS, defined as

$\mathrm{DegC}_{\mathrm{BESS}} = \mathrm{DegC}_{\mathrm{BESS,specific}} \cdot \Delta t \cdot \sum_{t=0}^{T} (P_{\mathrm{BESS,c}}(t) + P_{\mathrm{BESS,d}}(t))$,

(25) where $\mathrm{DegC}_{BESS,specific}$ represents the specific BESS degradation costs. These costs are calculated as a function of the maximum number of cycles until the end of life $n_{\mathrm{cycles}}$, the depth of discharge DoD, and the roundtrip efficiency $\eta_{\mathrm{BESS}}$, according to Eq. (26):

$$\mathrm{DegC}_{\mathrm{BESS,specific}} = \frac{CAPEX_{\mathrm{BESS,specific}}}{n_{\mathrm{cycles}} \cdot 2 \cdot \mathrm{DoD} \cdot \eta_{\mathrm{BESS}}}. \quad (26)$$

The OAP monetizes electricity and hydrogen revenues while internalizing water supply and electrolyzer degradation costs of the electrolyzer and BESS, thereby incentivizing profit-maximizing operation that accounts for both immediate market returns and long-term capital preservation.

*Page 17, line 443:*

2.3.2 MIL electrolyzer degradation model

*Page 21, line 526:*

For the BESS we assume a lifetime of 10 years (Lynus, 2026) 30 years (Ibáñez-Rioja et al. 2025)

*Tabel 1:*

| | | | |
|---|---|---|---|
| Lifetime $T_{\mathrm{BESS}}$ | 10 | years | - |
| Specific CAPEX $CAPEX_{\mathrm{BESS,specific}}$ | 560 | € $\mathrm{kWh}^{-1}$ | Cole et al. (2025) |

*Page 27, line 627:*

In contrast, the BESS undergoes approximately one cycle per day under the variable price operation optimization. Given a nominal cycle life of 8,000 cycles, this operational frequency corresponds to an expected service life of around 22 years. Consequently, the resulting BESS degradation costs are minor compared to both the OAP and the electrolyzer degradation costs, as seen in Fig. 9. Furthermore, this evaluation indicates that the baseline assumption of a 10-year lifetime utilized during the design optimization is highly conservative.

*Page 29, line 697*:

While the BESS effectively protects the electrolyzer stack from premature aging, the BESS itself is subject to wear-and-tear through cycling (Xu et al. 2018). BESS degradation, however, was only implicitly accounted for in the design method through a conservative assumption of a calendar life of 10 years. Cycle-induced BESS degradation was not explicitly modelled but could lead to an increase in neglected in this study, likely leading to an underestimation of the LCOH.

**RC** **The design problem is nonlinear and likely non-convex, and the paper uses the Nelder–Mead algorithm after an exploratory design-space sweep. The authors should provide more information on the optimization bounds, initialization, stopping criteria, convergence tolerance, number of function evaluations, and whether multiple starting points were tested. In addition, terms such as "global optimum" should be avoided unless global optimality can be justified.**

**AR** We agree that the Nelder-Mead algorithm, as a local derivative-free search method, may be susceptible to local optima in potentially non-convex design spaces. To address this we have replaced the previous optimization approach with a differential evolution (DE) algorithm. DE is a population-based, stochastic optimizer that is better suited for the non-linear characteristics of the wind-hydrogen-battery design space. Replacing the optimization algorithm led to minor variations in the results. Consequently, Figures 7 to 10, Table 2 and 3, and their descriptions have been revised. Additionally, we have included the requested technical details of the optimization setup and avoided the term "global optimum". Although the results shifted slightly during the revision process, the fundamental findings remain unchanged.

**AC**

*Page 6, line 161:*

Within the design optimization method the design parameters $P_{\mathrm{El}}$ and $W_{\mathrm{BESS}}$ are iteratively adjusted by the Nelder-Mead differential evolution (DE) algorithm (Storn and Price 1997), which that is further described in Sect. **Fehler! Verweisquelle konnte nicht gefunden werden.** (Lagarias et al. 1998).

*Page 6, line 168:*

Before the termination criterion for the Nelder–Mead DE optimization is verified…

*Page 10, line 262:*
It is solved using the ~~Nelder–Mead~~ DE algorithm~~, a derivative-free method commonly applied to NLPs (Scholz 2018)~~. Due to its stochastic search strategy, this population-based approach enables a robust exploration of the complex design space while mitigating dependency on the initial starting point. Consequently, the best identified solution within the predefined termination criteria is reported as the optimal configuration. The search space for both the electrolyzer rated power and the BESS capacity is constrained between 0 % and 30 % of the wind farm rated power based on the boundary insights from Chatzistlyianos et al. (2025) and Reichartz et al. (2024). A random solver strategy was selected to maintain population diversity, utilizing a population factor of 15 and a crossover probability of recombination of 0.7 to balance vector mutation and target retention. To bypass local sub-optima and prevent population stagnation, dynamic scaling via dithering was applied with a mutation parameter of (0.5, 1). Computational execution was parallelized across all available CPU cores with the parameter workers set to minus one, which requires a synchronous population update scheme. Lastly, the optimization run was bounded by a maximum of 100 generations and a relative convergence tolerance of 0.001 to limit the computational overhead of the underlying hourly time-series optimization, while a fixed random seed of 1 ensures full numerical reproducibility of the optimization trajectories.

*Page 23, line 546:*
However, to identify ~~the region where the global optimum likely resides,~~ a near-optimal solution the design space is explored by varying the design variables $P_{\mathrm{El}}$ and $W_{\mathrm{BESS}}$ within the differential evolution optimization algorithm. ~~Therefore, the ratio of the electrolyzer rated power to the WF rated power is varied from 0.015 to 1.0 and the BESS capacity from 0.0 to 1.0 in 0.015 increments. Thus, an increment corresponds to a deviation of 1 MW respectively 1 MWh.~~

*Page 23, Figure 7:*

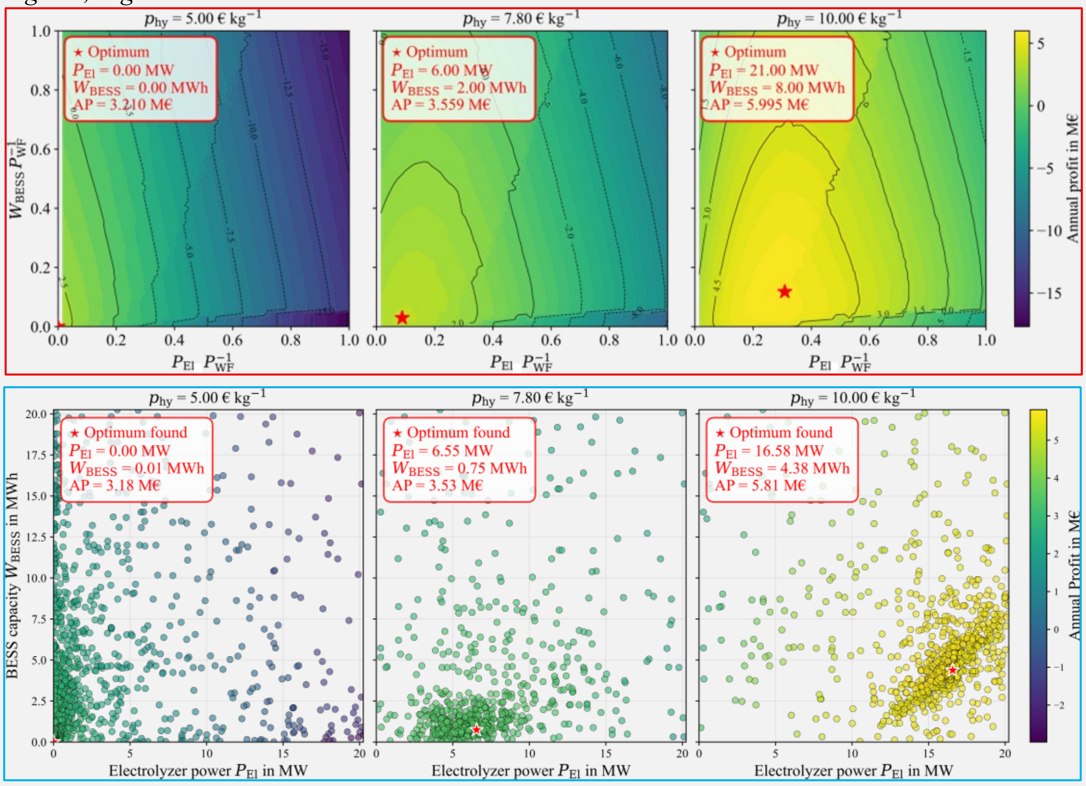


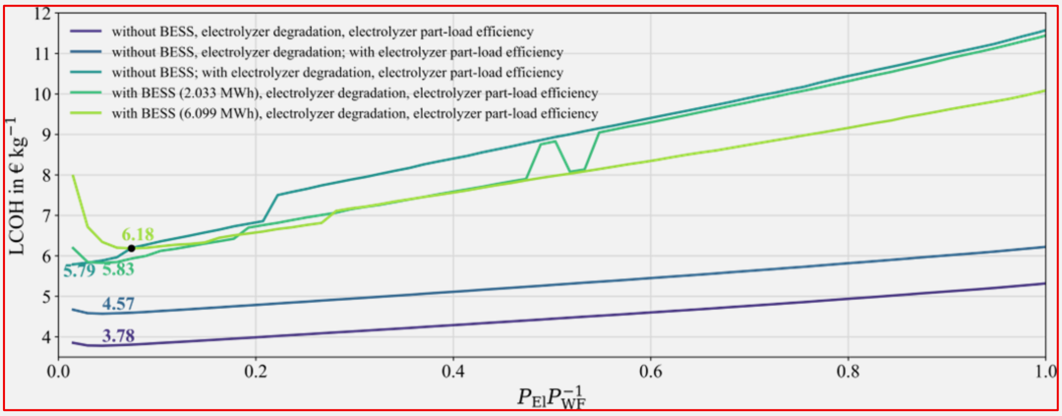

Figure 7: ~~Annual profit as function of electrolyzer rated power and rated BESS capacity over wind farm rated power for three different hydrogen prices.~~
Figure 7: Design space exploration of annual profit via differential evolution for three different hydrogen prices.

**Fehler! Verweisquelle konnte nicht gefunden werden.** illustrates the strong dependence of the optimal ~~HWF~~HPP design on the assumed hydrogen price. The results indicate that the ~~global~~ optimum found shifts toward larger electrolyzer and BESS capacities as the hydrogen price increases. With a constant hydrogen price of 5.0 € kg$^{-1}$, the maximum AP occurs at neglectable electrolyzer and BESS sizes, because ~~for~~ the stand-alone WF remains the more profitable option. This AP without electrolyzer and BESS is calculated as the product of AEP and the difference between the RV and the LCOE amounting to 3.21 M€ $a^{-1}$. ~~A threshold price of 7.0 € $kg^{-1}$ is required for a configuration with 1 MW and 0 MWh to achieve a higher AP than the stand-alone WF. Below this hydrogen price level, the implementation of a HWF does not yield economic benefits under the given assumptions.~~ As seen in the middle and right panels of **Fehler! Verweisquelle konnte nicht gefunden werden.** the hydrogen price of 7.8 € $kg^{-1}$, results in an optimal configuration shift to 6.55 MW and ~~2~~0.75 MWh, while at 10 € $kg^{-1}$ it further increases to ~~21~~16.58 MW and ~~8~~4.38 MWh. ~~The results indicate that variations in the electrolyzer rated power have more significant impact on the AP than variations in the BESS capacity.~~ The optimum identified in the central panel of **Fehler! Verweisquelle konnte nicht gefunden werden.** with $p_{hy}$ equals 7.8 € $kg^{-1}$ serves as ~~the initial~~ configuration for the following observations ~~design optimization method, which employs the Nelder-Mead algorithm described in Sect. 2.2 for the given use case of Sect. 3.1~~. ~~The optimized design variables, as well~~ Additional results as the mean AP, mean annual revenues, mean AHP, and TOTEX determined over the observation period, are detailed in Table 1.

**Table 1: Design optimization results of the described use case over the entire observation period.**

| Output | Value | Unit |
|---|---|---|
| ~~Optimized electrolyzer rated power~~ | ~~6.435~~ | ~~MW~~ |
| ~~Optimized BESS capacity~~ | ~~2.034~~ | ~~MWh~~ |
| Mean AP | 3.53 ~~3.57~~ | M€ $a^{-1}$ |
| Mean annual hydrogen profit | 1.09~~1.12~~ | M€ $a^{-1}$ |
| Mean annual electricity profit | 2.44~~2.45~~ | M€ $a^{-1}$ |
| Mean AHP | 642~~626~~ | t $a^{-1}$ |
| Mean annual hydrogen revenue | 5.01~~4.88~~ | M€ $a^{-1}$ |
| Mean annual electricity revenue | 9.81~~9.84~~ | M€ $a^{-1}$ |
| LCOH | 6.10~~6.01~~ | € ${kg_{H_2}}^{-1}$ |
| TOTEX without WF | 45.84~~44.20~~ | M€ |
| TOTEX electrolyzer | 42.10~~40.00~~ | M€ |
| TOTEX pipeline system incl. water supply | 1.59~~1.56~~ | M€ |
| TOTEX electricity supply | 1.39~~1.37~~ | M€ |
| TOTEX BESS | 0.76~~1.27~~ | M€ |

~~The optimized design variables obtained are an electrolyzer rated power of 6.435 MW and a BESS capacity of 2.034 MWh.~~ The AP of 3.53~~7~~ M€ $a^{-1}$ of the ~~HWF~~HPP is composed of the annual electricity profit by a share of approximately two-third and the annual hydrogen profit by one-third. For the given hydrogen price, the AP of the ~~HWF~~HPP is about 10~~11~~ % above the AP of the stand-alone WF, demonstrating that the ~~HWF~~HPP can have a significant impact on the economics of the system installed at the given WF site. The annual electricity revenue accounts for 9.814 M€ $a^{-1}$, representing approximately two thirds of the total revenues, while hydrogen sales contribute the remaining one third with 5.01~~4.88~~ M€ $a^{-1}$, which is consistent with the relative contributions to the AP. The TOTEX without the existing WF respectively of the added hydrogen system amount to 45.84~~44.20~~ M€ over the entire observation period. The largest share of TOTEX is associated with the electrolyzer, driven primarily by variable electrolyzer OPEX in the form of electricity procurement costs, which account for about ~~64~~69 % of the electrolyzer TOTEX. The remaining costs are significantly lower. This cost distribution emphasizes that the profit optimization of the ~~HWF~~HPP depends primarily on the electricity procurement and secondary on the electrolyzer investment and replacement costs, rather than on the cost reduction of peripheral components.



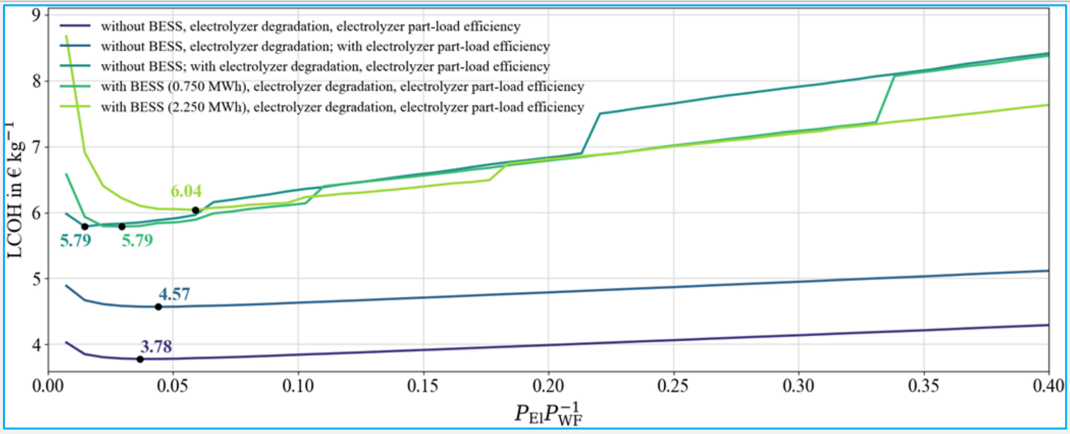



**Figure 3: LCOH over the ratio of electrolyzer rated power to wind farm rated power for four different modeling approaches and two different BESS sizes.**

A comparison of the minimum LCOH values of the model variants without BESS shows that neglecting electrolyzer degradation leads to an underestimation of the LCOH by approximately 21 %, while neglecting both degradation and partial-load efficiency results in an underestimation of about 35 %. These results highlight the critical importance of accurately representing both degradation effects and part-load efficiency in electrolyzer model~~l~~ling. By ~~A~~adding a BESS capacity of 0.750~~2.033~~ MWh, that was previously identified as optimum for the AP maximization for the given use case, ~~actually leads to an increase in~~ the LCOH ~~by less than one percent~~ remain at a constant level while ~~increasing~~ the AP increases by 7~~5~~ % in this scenario. While the incremental hydrogen yield is ~~in~~sufficient to offset the additional BESS-related TOTEX, resulting in constant ~~a marginal~~ LCOH ~~increase~~, the system benefits from enhanced operational flexibility. Consequently, the BESS effectively increases the AP by capturing higher market revenues ~~that outweigh the rise in levelized production costs~~. An increased BESS capacity shifts the LCOH minimum to higher electrolyzer capacities while ~~further~~ increasing LCOH. Ultimately, these findings underscore that the choice of the objective function is pivotal for the optimal sizing of both the electrolyzer and the BESS, as it fundamentally dictates whether the integration of a BESS is perceived as a profit benefit or a cost driver.

A technical driver behind this economic trade-off is the BESS ability to mitigate electrolyzer degradation. Specifically, the operation strategy assumed in Sect. **Fehler! Verweisquelle konnte nicht gefunden werden.** results in an annual electrolyzer degradation, calculated according to Sect. **Fehler! Verweisquelle konnte nicht gefunden werden.**, for the in Sect. **Fehler! Verweisquelle konnte nicht gefunden werden.** presented HPP system of 0.1294~~0.1138~~ V a$^{-1}$. This TAD corresponds to degradation costs of 0.5900~~0.586~~ M€ a$^{-1}$, when converted according to Eq. (24). If the BESS is removed, the TAD increases to 0.1577 V a$^{-1}$, increasing the degradation cost by 0.1290~~0.226~~ M€ a$^{-1}$. The electrolyzer degradation with and without BESS divides into the different operation modes according to Table 2.

**Table 2: Share of the total annual electrolyzer degradation depending on the electrolyzer operation modes with and without BESS.**

| Operation mode | With BESS (0.75 MWh): TAD = 0.1294~~0.1138~~ V a$^{-1}$ | | Without BESS: TAD = 0.1577 V a$^{-1}$ | |
|---|---|---|---|---|
| | AD in V a$^{-1}$ | AD share of TAD in % | AD in V a$^{-1}$ | AD share of TAD in % |
| rated | 0.0145 | 11.18~~12.74~~ | 0.0145 | 9.17~~9.20~~ |
| partl | 0.0012~~0.0019~~ | 0.96~~1.66~~ | 0.0009~~0.0008~~ | 0.56~~0.54~~ |
| off | 0.0021~~0.0015~~ | 1.61~~1.35~~ | 0.0026~~0.0025~~ | 1.63~~1.61~~ |
| fluct | 0.0675~~0.0665~~ | 52.19~~58.43~~ | 0.0666~~0.0668~~ | 42.21~~42.38~~ |
| stop | 0.0441~~0.0294~~ | 34.06~~25.82~~ | 0.0732~~0.0730~~ | 46.43~~46.28~~ |

The fluctuating operation mode is the dominant driver of electrolyzer degradation in the system with BESS. However, removing the BESS leads to a significant increase in the TAD by more than a fifth~~third~~. This is primarily driven by the degradation from start-stop cycles, which increases by about 60 % ~~more than doubles from 0.0294 V a$^{-1}$ to 0.0730 V a$^{-1}$~~. Furthermore, the AP of the System without BESS decreases to 3.4 M€, representing a 3.7~~4.7~~ % reduction compared to the configuration featuring a 0.75~~2.034~~ MWh BESS. These findings underline the effectiveness of the BESS within the implemented operation strategy by buffering volatile WF power. The battery prevents frequent shutdowns and ensures a more continuous hydrogen production, thereby substantially mitigating cycle-induced degradation of the electrolyzer. While the BESS integration entails additional CAPEX, these costs are offset over the system's operational period by reduced electrolyzer degradation costs and increased hydrogen revenues, even when limited to a buffering operation strategy.

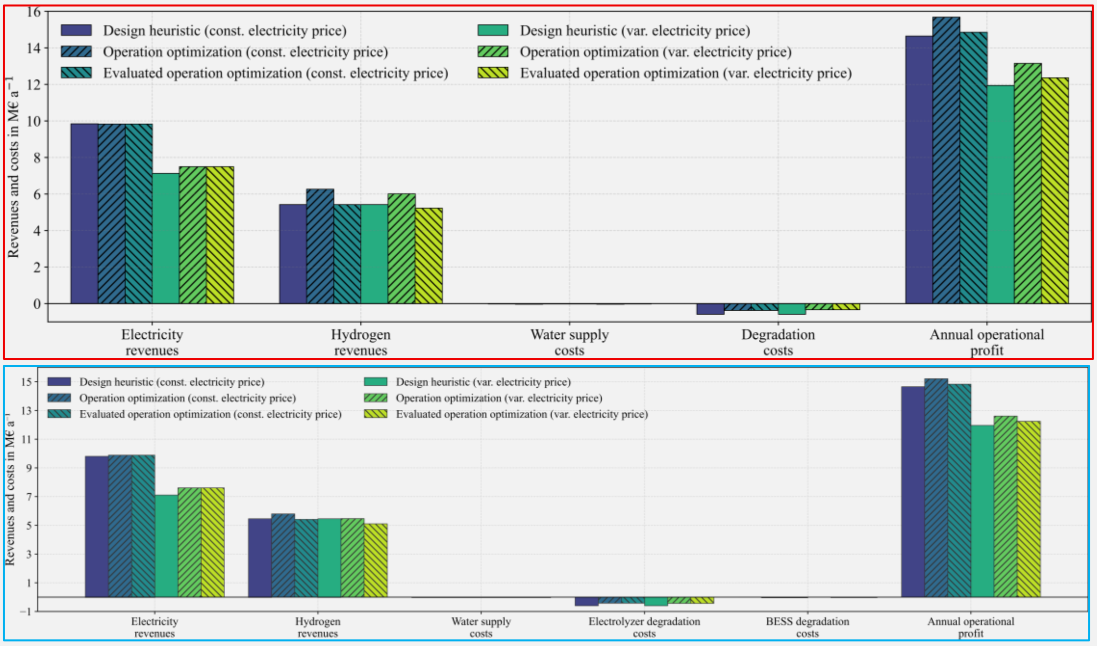



**Figure 4: Comparison of the annual operational profit and its shares of the design optimization, the MIL operation optimization, and its degradation evaluation for constant and variable electricity prices.**

**Figure 4** shows that the assumed constant electricity price in the design optimization leads to a systematic overestimation of electricity revenues and, consequently, of the OAP by 23 % when compared to variable electricity price conditions of 2024. This highlights the limitations of design-stage economic assumptions when applied to real-world market environments with pronounced price volatility. In addition, the electrolyzer degradation costs associated with the operating strategy assumed during the design optimization amount to 0.59 M€ $a^{-1}$and can be reduced by about 38~~44~~ % through the proposed operational optimiz~~s~~ation under variable price conditions. This reduction underlines the strong influence of operational control on component ageing and long-term economic performance. In contrast, the BESS undergoes approximately one cycle per day under the variable price operation optimization. Given a nominal cycle life of 8,000 cycles, this operational frequency corresponds to an expected service life of around 22 years. Consequently, the resulting BESS degradation costs are minor compared to both the OAP and the electrolyzer degradation costs, as seen in Fig. 9. Furthermore, this evaluation indicates that the baseline assumption of a 10-year lifetime utilized during the design optimization is highly conservative.

Neglecting degradation-induced efficiency losses and using a piecewise linearized efficiency of the electrolyzer within the operation optimization leads to an overestimation of hydrogen revenues by 7~~15~~ % under variable electricity price conditions, relative to the revenues obtained from the subsequent degradation evaluation. Initially, the MIL operation optimization suggests a significant economic potential, with a projected OAP approximately 5~~10~~ % higher than that of the design heuristic. Despite the subsequent revenue correction due to degradation effects and efficiency linearization, the evaluated OAP remains above the value calculated in the design phase, reaching 102~~104~~ % under variable electricity prices and 101 % under constant electricity prices. This demonstrates that MIL operational optimization, even when neglecting degradation-related efficiency losses, can slightly enhance economic performance relative to the simplified operation assumptions in the design optimization. However, the gap between the initial 5~~10~~ % projection and the evaluated 1 % to 2~~4~~ % gain highlights the ~~clear~~ potential for further improvements through a more comprehensive representation of degradation effects within the economically optimum operation of the HPP.

To analyse the impact of the assumed hydrogen price on the optimal ~~HWF~~HPP operation and to evaluate the discrepancies between the system components operation of the design optimization and the MIL operation optimization,

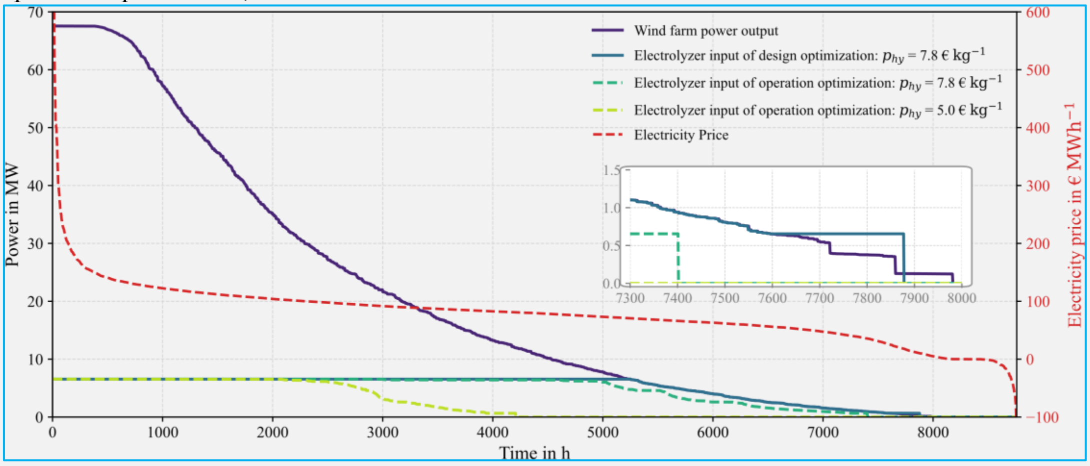
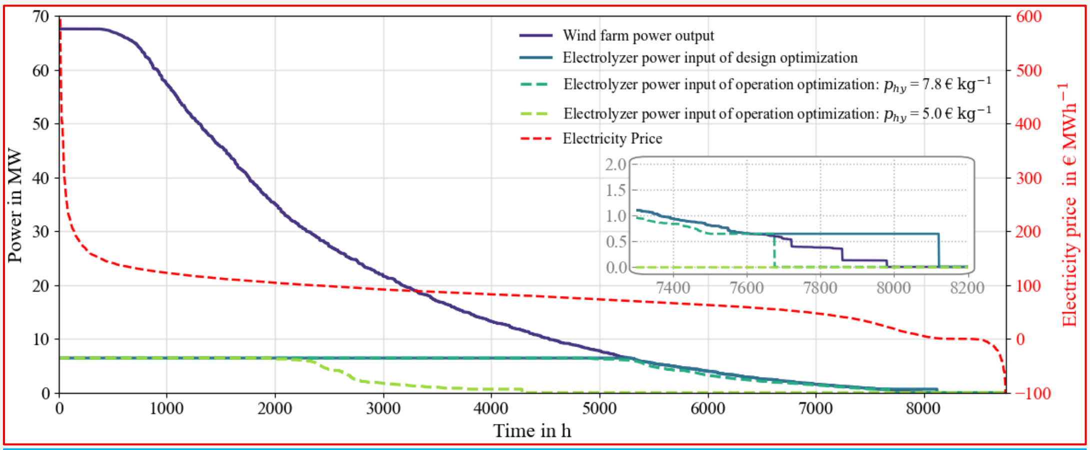



Figure **5** presents different annual load duration curves. The figure illustrates the electrolyzer power input for varying hydrogen price scenarios alongside the WF power output. Additionally, the day-ahead electricity market price of 2024 is included and plotted in descending order.



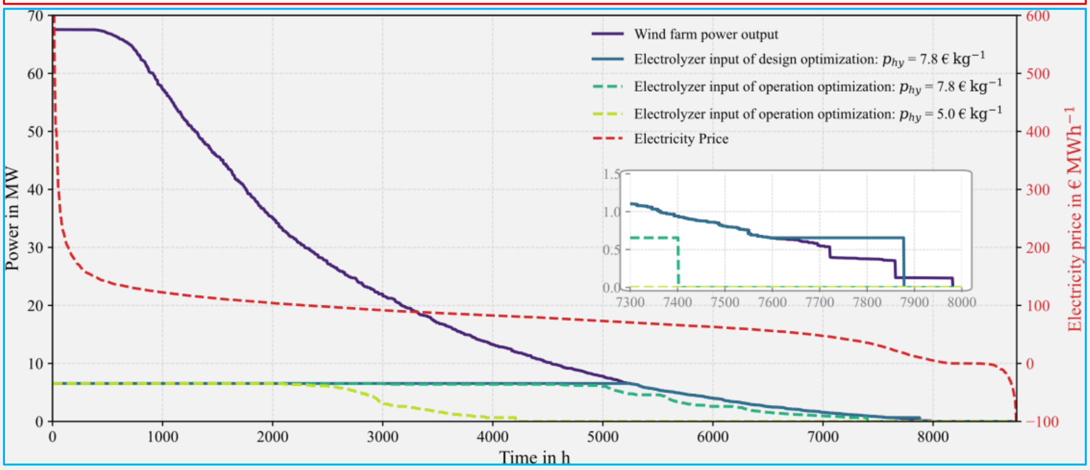




**Figure 5: Sorted load duration curves of the WF power output, the electrolyzer power input of the design optimization, and for the MIL operation optimization for two different hydrogen price scenarios, and the sorted electricity price over one year.**

The comparative analysis of the sorted load duration curves, as illustrated in

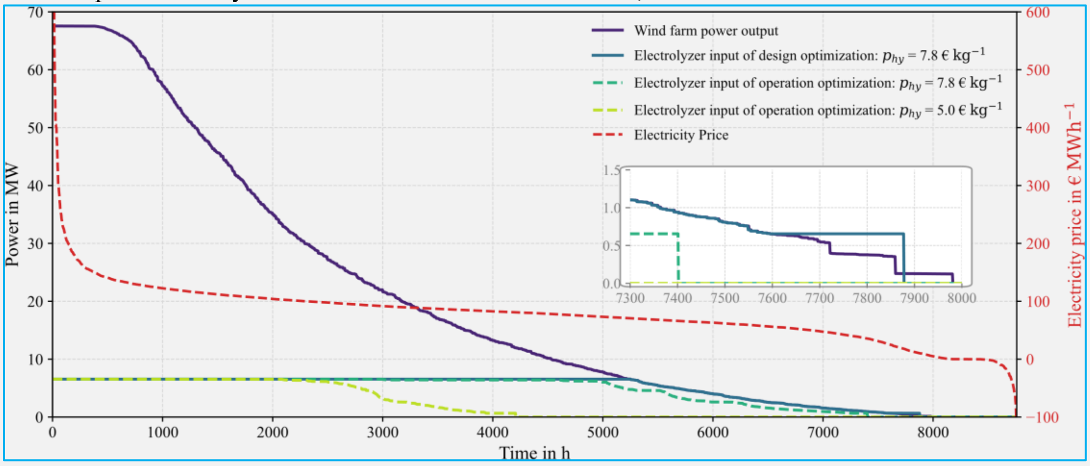



Figure **5**, reveals that the operational characteristics of the design heuristic and the operational optimization differ ~~only~~ marginally at a hydrogen price of 7.8 € kg$^{-1}$. Specifically, the design heuristic (~~dark~~ solid blue line) accounts for 6,375 ~~6,418~~ full load hours (FLH) per year, while the operational optimization (dashed teal ~~solid~~ line) reaches 5,892 ~~6,213~~ FLH. This high degree of similarity is primarily attributed to the fact that the assumed hydrogen price is significantly higher than the average electricity day-ahead market price of 79.6 € MWh$^{-1}$. Under these conditions, the marginal revenue from hydrogen production mostly exceeds the opportunity costs of direct electricity sales, incentivizing the system to maximize hydrogen output regardless of the specific operation approach. ~~Even~~ However, when reducing the hydrogen price to 5.0 € kg$^{-1}$ (dashed light green line), the optimized electrolyzer operation shifts to 3,157 ~~2,858~~ FLH~~, the economic performance of the design heuristic alters.~~ Despite the design operation strategy's price-independent nature and the resulting inability to account for fluctuating market signals, the evaluated OAP ~~annual operational profit~~ achieved through MIL optimization exceeds that of the static design ~~optimization~~ operation under variable electricity price conditions by more than ~~only 4.5~~ 9 % at the lower hydrogen price scenario. This suggests that ~~while~~ the heuristic remains active during periods where market electricity prices exceed the marginal revenue of hydrogen production, resulting in ~~the~~ associated economic losses ~~are largely mitigated by the overall system design~~ compared to the price-dependent MIL operation optimization. ~~Although the operation optimization selectively decreases the input power of the electrolyzer during high-price electricity periods, the marginal profit gain remains limited.~~ It must be noted, however, that the ~~high~~ ~~accuracy of~~ results of the operation optimization ~~heuristic~~ compared to ~~within~~ the design optimization observed here are ~~is~~ specific to the investigated use case.

*Page 29, line 684:*
In this context, the design optimization identified a ~~global optimum~~ near-optimal solution for the electrolyzer rated power and BESS capacity of the investigated use case.

*Page 30, line 720:*
Alternatively, nonlinear optimization could directly integrate degradation effects into the decision-making process, although this significantly increases computational effort ~~and may hinder the identification of a global optimum~~.

| | |
|---|---|
| **RC** | **The robustness of the case-study conclusions should be strengthened. The case study is based on one specific wind farm, one wind time series, German 2024 day-ahead electricity prices, and a fixed hydrogen price. However, the optimal electrolyzer and BESS sizing, as well as the performance gap between the rule-based heuristic and the MIL dispatch optimization, are likely sensitive to wind-resource profiles, electricity price volatility, and hydrogen price assumptions. To strengthen the conclusions, the authors are encouraged to include sensitivity analyses using at least one additional wind year, electricity price year, or hydrogen price scenario.** |
| **AR** | We thank the reviewer for this constructive comment regarding the sensitivity of our case-study results to external conditions. We fully agree that the optimal sizing configurations are highly dependent on external inputs. To address this a sensitivity analysis for the hydrogen price is integrated into the study, as shown in Figure 7. These results clearly demonstrate that the hydrogen price has a massive impact on the optimal capacities of $P_{\mathrm{El}}$ and $W_{\mathrm{BESS}}$, which underscores that the sizing configuration reacts highly sensitively to external economic drivers. |

| | |
|---|---|
| | Because the design results cannot be classified as universally robust against shifting external factors, we agree that terms like "robust" or "global optimum" were misleading in this context. Consequently, we have revised the manuscript to eliminate these terms. Additionally, we have now explicitly acknowledged these sensitivities as a limitation in the revised discussion section.<br><br>The primary focus of this paper is the high-fidelity modeling of the internal technical component specifications such as dynamic stack degradation and non-linear part-load efficiency curves rather than a comprehensive multi-year climatic uncertainty analysis. Developing a fully robust sizing framework capable of optimizing across multi-year weather and price scenarios is a vital next step, but it remains outside the scope of this model specific paper. |
| **AC** | |
| | *Page 2, line 36:*<br>Furthermore, it demonstrates that a rigorous consideration of the operational strategy is necessary for a ~~robust and~~ reliable system assessment to account for volatile external factors.<br><br>*Page 22, line 546:*<br>However, to identify ~~the region where the global optimum likely resides,~~ a near-optimal solution the design space is explored by varying the design variables $P_{El}$ and $W_{BESS}$ within the differential evolution optimization algorithm. ~~Therefore, the ratio of the electrolyzer rated power to the WF rated power is varied from 0.015 to 1.0 and the BESS capacity from 0.0 to 1.0 in 0.015 increments. Thus, an increment corresponds to a deviation of 1 MW respectively 1 MWh.~~<br><br>*Page 23, line 551:*<br>The results indicate that the ~~global~~ optimum found shifts toward larger electrolyzer and BESS capacities as the hydrogen price increases.<br><br>*Page 29, line 684:*<br>In this context, the design optimization identified a ~~global optimum~~ near-optimal solution for the electrolyzer rated power and BESS capacity of the investigated use case.<br><br>*Page 30, line 720:*<br>Alternatively, nonlinear optimization could directly integrate degradation effects into the decision-making process, although this significantly increases computational effort ~~and may hinder the identification of a global optimum~~.<br><br>*Page 30, line 724:*<br>Additionally, this work did not explore variations in electricity price profiles or wind generation time series~~, both of which can exert a substantial influence on optimal operating behaviour~~. These external drivers can exert a substantial influence not only on the optimal operating behaviour, but also on the resulting component sizing configurations and the performance gap between the rule-based heuristic and the MILP dispatch optimization.<br>*Page 30, line 730:*<br>To derive reliable investment decisions, a hybrid wind farm design must demonstrate robustness against external factors. Therefore, the integration of adaptive operational optimization directly into the sizing process can ensure that the system responds to market volatility or volatile wind power generation, providing a ~~robust~~ basis for identifying the optimal HPP design even under uncertain external conditions. |

| | |
|---|---|
| **RC** | **Correct spelling and wording issues, for example: "Bevor" → "Before," "eighter" → "either," "prize cannibalization" → "price cannibalization," "European Comission" → "European Commission," "archivable electricity price" → probably "achievable electricity price," "reasonably solution" → "reasonable solution," and "the integrate of adaptive…" → "the integration of adaptive…", etc.** |
| **AR** | All comments have been addressed according to the reviewer's suggestions. |
| **AC** | |
| | *Page 5, line 128:*<br>~~Bevor~~ Before starting the design optimization<br><br>*Page 2, line 63:* |

... Schnuelle et al. (2020) and Fabianek and Madlener (2024) ~~eighter~~ evaluated given…

*Page 2, line 46:*
Meanwhile, WF operators encounter revenue declines due to ~~prize cannibalization~~ price cannibalization and high price volatility (Bechmann und Quick 2025).

*Page 2, line 40:*
To achieve the European Union's climate target of reducing greenhouse gas emissions by 55 % by 2030 (European Parliament and Council 2021), the share of renewable energy in the energy mix is planned to be increased to 42.5 % and the production of 10 million tons of green hydrogen is targeted by 2030 ~~(European Comission)~~ (European Commission 2026)

*Page 1, line 27:*
Firstly, the assumption of a constant ~~archivable~~ achievable electricity price over the systems lifetime leads to a 23 % overestimation of annual operational profits when compared to the more realistic electricity sales at the German day-ahead market in 2024.

*Page 11, line 301:*
Nevertheless, this strategy is employed to obtain a ~~reasonably~~ reasonable solution.

*Page 30, line 731:*
Therefore, the ~~integrate~~ integration of adaptive operational optimization directly into the sizing process can ensure that the system responds to market volatility or volatile wind power generation, providing a robust basis for identifying the optimal HPP design even under uncertain external conditions.