Information on how to read the document

- RC: Referee Comment
  - Pages and lines in the referee comments refer to the manuscript submitted before the review process, as we did not want to change referee 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 here 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.

Review 1

Abstract

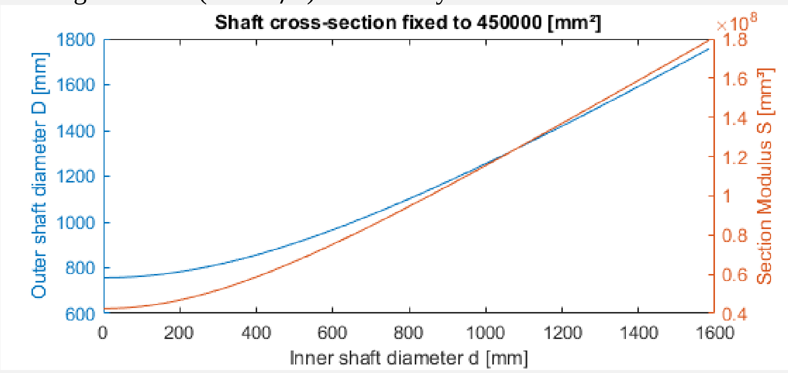
RC 1	Line 18 Instead of the somewhat vague "greatly reduced" I think it would be better to state the figure from the Conclusions such as "reduced by X%". Please see later comment on the Conclusions though regarding the exact percentage.
AR	We added the percentage to the line – the percentages refer to the mass of the machined shaft
AC	Lines 17-18 For the hollow forged rotor shaft to be comparable to casting regarding manufacturing costs, the forging surcharges need to be ~~greatly reduced~~ less than 50% of the shaft mass.

RC 2	Line 19 As noted in the Conclusions, I think it would be beneficial to the reader to add the caveat that "the GWP of hollow forging is comparable to casting and each are actually less than one-third of the GWP of the entire MBU."
RC 14	Line 18 I think it would be clearer to add "…the manufacturing GWP of hollow forging…"
AR	As the main bearings are quite heavy (oversized), the wording was changed to around one-third (the shaft share would be larger for smaller bearings) and added to the text
AC	Lines 18-20 Due to the shortened heat treatment of AHD steels and the use of green steel, the manufacturing GWP of hollow forging is comparable to casting and makes up around one-third of the GWP of the entire MBU.

1 Introduction

RC 3	Line 37 I am not sure I understand the explanation here regarding a higher inner shaft diameter, section modulus, area, and outer shaft diameter. A fixed section area A and outer diameter D means a fixed inner shaft diameter d as well. In looking at Figures 2 and 3, it appears the outer diameters are similar (1000 mm), but the inner diameter and section area of the AHD shaft in Figure 2 is smaller than the case diameter shaft in Figure 3.
AR	Regarding the section modulus, the explanation assumes that the cross-section area of the shaft (=annulus) is fixed. In this case the outer diameter is a function of the inner diameter ($D = \sqrt{4A/\pi - d^2}$ and similarly the section modulus (S = f(A, d)). In this case, a larger inner diameter results in a larger section modulus (see the following figure), which enables the transfer of higher

bending moments ($\sigma = M/S$) or reversely a cross-section reduction.



As cast iron has a lower tensile strength than AHD steel, an AHD steel shaft can have a larger inner diameter than a cast shaft for the same outer diameter and loads.

→ *Line changed for better understanding*

AC Lines 38-39

A larger inner shaft diameter (d) enables higher section modulus ($S_{Bending}$, see Eq. (1)) for a fixed shaft cross~~-~~ section (A; ~~with~~ outer shaft diameter D calculated given Eq. (2)).

3.2 MBU designs and power density analysis

RC 4 I believe the main points of this section are to summarize the design characteristics of the original maxcap 141 MBU, then the hollow forged shaft MBU, then the cast shaft MBU. I think the main point of including the maxcap 141 characteristics is to show that the other designed MBUs discussed in the remainder of the paper are "similar enough" to the actual maxcap 141. Having said that, I'll admit that I got a bit lost by the relatively long text explanations. A summary mass Table I think would be really helpful and shorten some of the text, especially as related to lines 145-162. Tables are used elsewhere in the article to good effect.

AR To improve readability, a table was inserted with the component masses as suggested.
Similarly, the letter symbols (masses) were simplified/removed from the text.
Cast variant section was shortened.

Note: New table effects numbering of following tables

AC Lines 138-141

The resulting hollow forged rotor shaft has a mass of 10.2 t ~~($m_{RS,HF}$)~~, the upwind and downwind bearings have a mass of 0.78 t ~~($m_{B1,HF}$)~~ and 4.38 t ~~($m_{B2,HF}$)~~ respectively, see Table 3. The mass of the bearing housings (including assembly components) is scaled based on the bearing masses using a factor of 2.92 taken from NREL's WISDEM / DrivetrainSE (Guo et al., 2015; National Renewable Energy Laboratory, 2024)~~, coming in at 2.3 t ($m_{H1,HF}$) and 12.8 t ($m_{H2,HF}$).~~

Line 142

Table 1: Mass comparison of the different MBU variants

Variant		Rotor shaft	Upwind main bearing	Downwind main bearing	Upwind main bearing housing*	Downwind main bearing housing*
maxcap 141 MBU	Mass (m) [t]	16.2	2.1	0.9	11.4	
MBU with AHD steel hollow forged rotor shaft	Mass (m) [t]	10.2	0.78	4.38	2.3	12.8
	Manuf. mass ($\overline{m}$) [t]	22.4	-	-	2.8	15.3
	Req. material ($\hat{m}$) [t]	26.5	-	-	3.0	16.9
MBU with cast rotor shaft (EN-GJS-400-18-LT)	Mass (m) [t]	16.2	0.79	4.38	2.3	12.8
	Manuf. mass ($\overline{m}$) [t]	19.4	-	-	2.8	15.3
	Req. material ($\hat{m}$) [t]	21.4	-	-	3.0	16.9

*Including main bearing assembly components

Lines 157-167

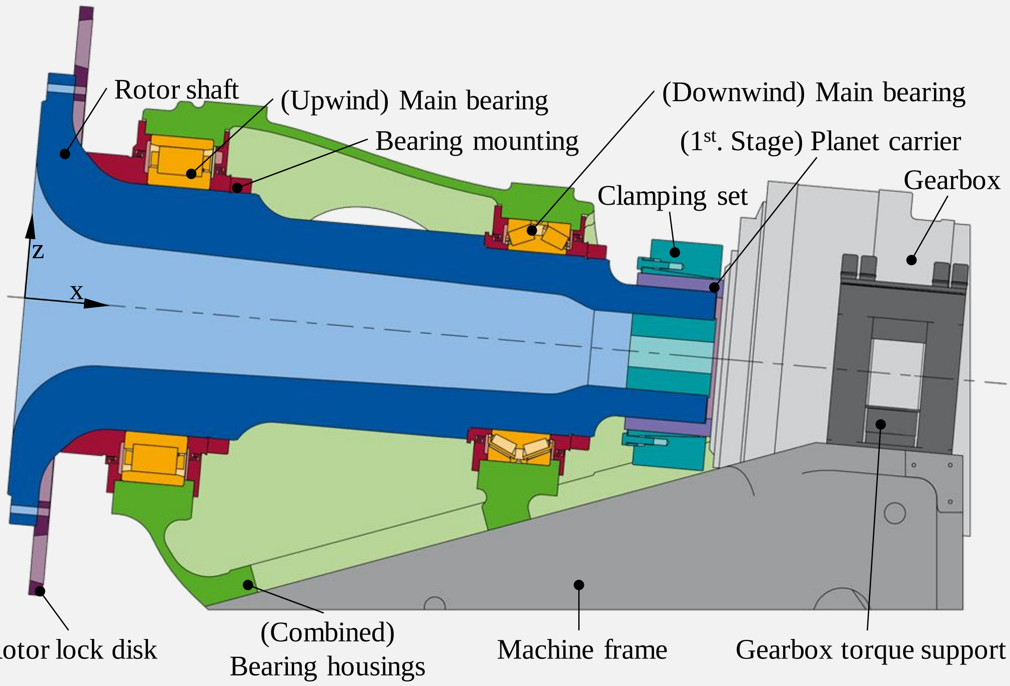
Consequently, the (post) forging mass of the shaft is 22.4 t ~~($m_{RS,HF}$)~~ and considering material losses during forging (see Sect. 3.3.1), around 26.5 t ~~($m_{RS,HF}$)~~ steel is required to produce the part.
In comparison, the cast rotor shaft has a mass of 16.2 t ~~($m_{RS,C}$),~~ and its upwind and downwind bearings 0.79 t ~~($m_{B1,C}$)~~ and 4.38 ~~t ($m_{B2,C}$) and the bearing housings 2.3 t ($m_{H1,C}$) and 12.8 t ($m_{H2,C}$)~~ respectively, see Table 3. As the mass difference between the predesigned cast shafts and original cast shafts is less than 0.1 t, the predesign tool produces a realistic predesign. The casting mass and required material of the rotor shaft and bearing housings are estimated with the casting percentages above.~~ is estimated to be 19.4 t ($m_{RS,C}$) based on a 20 % postprocessing~~

<table>
<tr><td></td><td>~~(machining) surcharge.~~ For simplification, the surcharge is assumed to be evenly distributed, leading to a 12.5 mm machining allowances around the shaft. In reality, the surcharge would be focused on functional surfaces such as the bearing seats or flange screw connection while non-functional surfaces might keep the casting finish. ~~Considering average casting losses of 10 % (due to e. g. oxidation, sprue), 21.4 t ($m_{RS,C}$) of material are required for casting the shaft.~~</td></tr>
</table>

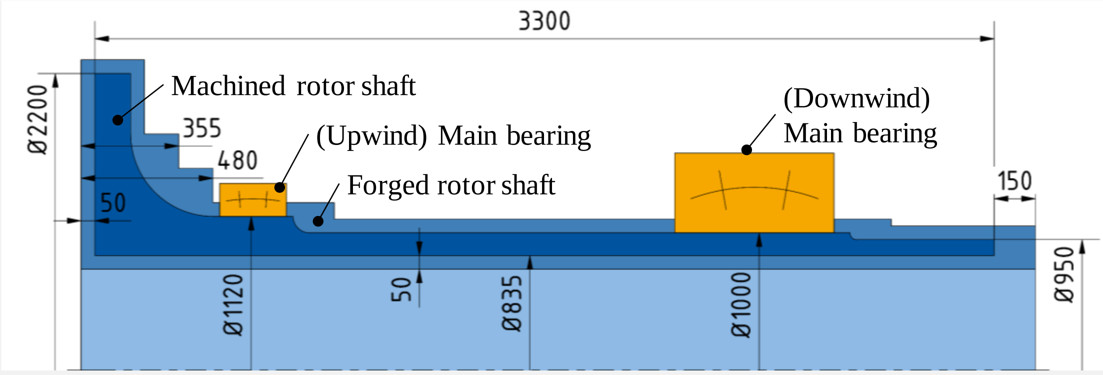
<table>
<tr><td>RC 5</td><td><u>Line 80 and Figure 1</u>
Terminology in this sentence, the figure, and the remainder of the paper are not quite the same, leading to a little bit of confusion. I believe it would be clearer to label both the “Upwind main bearing” and “Downwind main bearing” rather than just one “Main bearing” in the figure. Are the assembly components the same as the red components? Also, the “Machine frame” is labeled twice for both the green and grey components, with the green component (I think) called the “Main bearing housing” in the remainder of the paper (for example, in Section 3.3.3 and Table 5) and the grey component separate and not in the scope of the study. Additionally, the text states “The bearing housings…connect…gearbox to the azimuth bearing”. I don’t believe this is correct: as far as I can tell from the figure the gearbox is only connected to the grey “Machine frame”, but not the “Main bearing housing”. But I could be wrong here. It does not seem to be worth mentioning the azimuth bearing, as it is not shown in the figure and not in the scope of the paper either.</td></tr>
<tr><td>AR</td><td>Adjustment of bearing labels in Figures 1-3

“Are the assembly components the same as the red components?” => Yes;
for the other variants, they are indirectly considered trough the bearing housing mass

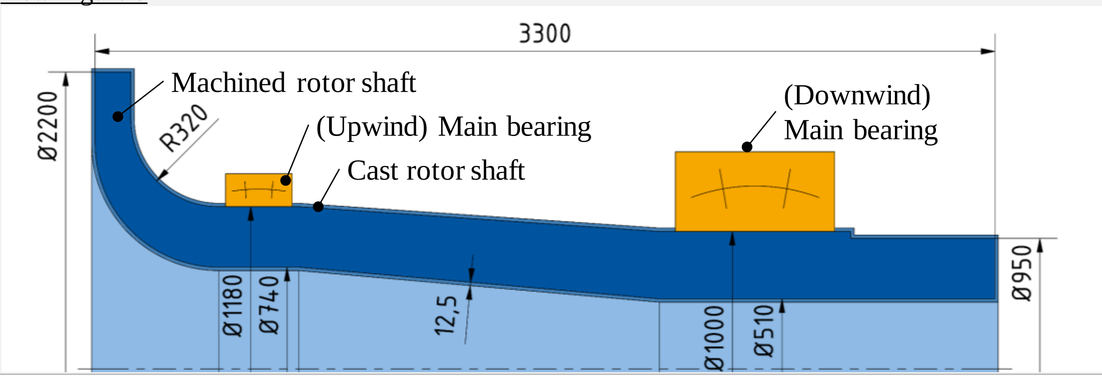
Adjustment of text and Figure 1 for better distinction between bearing housing and machine frame</td></tr>
<tr><td>AC</td><td><u>Lines 83-85</u>
The bearing housings are ~~integrated into the~~ combined into one cast ~~machine~~ frame, which is connected to the machine frame ~~and connect both main bearings and the gearbox to the azimuth bearing of the nacelle~~ (see Fig. 1).</td></tr>
<tr><td></td><td><u>New Figure 1</u>



<u>New Figure 2</u></td></tr>
</table>



New Figure 3



RC 6	Line 85 Not being an expert in this area, I am not familiar with the term "…requires a surface surcharge…". Can this be explained a bit? Does this effectively mean a "…requires a higher wall thickness…"?
AR	The word surface surcharges mean the added material for forging/casting to ensure that the final geometry can be machined within the required tolerances from the forged/cast geometry. A more general term for this should be allowance or oversize. See also Review 3 – RC 2
AC	Lines 89-91 Sand casting requires a surface surcharge (allowance) of up to 50 mm, approximately 20 % of the shaft mass, and 10 % additional material for sprue and other material loses (Weiß, R., 2024)

3.3.1 (Hollow) forging manufacturing costs

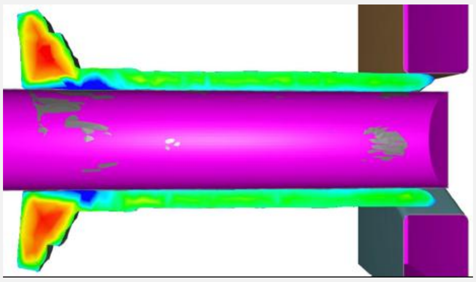
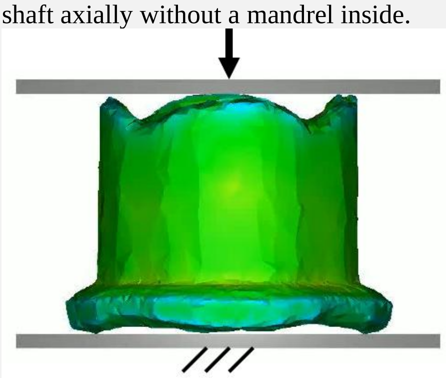
RC 7	Lines 199-203 Is it a correct understanding that the cost of the drilling of the solid forged shaft is not included in the analysis?
AR	The postprocessing (machining) cost are relatively small compared to the total shaft manufacturing costs. Given the *KNIGHT* references (lines 174-175), they make up around 10% of the total costs. For solid forging, the required material for forging includes the material which is later drilled out. As the costs scale with the mass, the additional bore material therefore also increases the machining costs. How the machining costs split up (sawing off shaft ends, drilling, turning, …) is not considered given the low cost share.
AC	*None*

3.3.2 Casting manufacturing costs

RC 8	Line 207 and Equation 6 It's minor, but is there a reason with the mass is denoted with subscript RS,C compared to Shaft in Equations 4 and 5?
AR	It was originally intended to distinguish the different components and manufacturing methods. →For better understanding, the subscripts were simplified. The casting costs per ton of required material were also added to Eq. 6 for better comparability to forging. (They were already included in Fig. 6)

AC	Line 192 Eq. (3) $Costs_{HF\|F}[€] = MC_{Alloy}\left[\frac{€}{t}\right] \cdot \hat{m}_{Shaft RS,*}[t] \cdot f_{TC} \cdot (1 + a_{HF} - a_{HT}) \cdot f_S$ Line 193 $\hat{m}_{Shaft RS,*}$ Line 222 Eq. (6) $Costs_C = 3\,750 \ldots 4\,250 \left[\frac{€}{t}\right] \cdot m_{Shaft RS,C}[t] \approx 2\,900 \ldots 3\,300 \left[\frac{€}{t}\right] \cdot \hat{m}_{Shaft}[t]$
	Lines 222-225 The cost is either based on the mass of the final shaft (m_{Shaft}), as – material surcharges for postprocessing (machining, ≈ 20 % of the shaft mass) and casting losses (≈ 10 % of the raw shaft mass) are already included via fixed factors – or the required material mass for casting ($\hat{m}_{Shaft}$).

3.3.5 Manufacturing cost comparison

RC 9	Line 242 Again, not being an expert in this area, I am not familiar with the term "…axial upsetting". Can a brief description be added here? Does this refer to standing the shaft upright, such that gravity has some compressive effect on it?
AR	General summary of the forging steps: During hollow forging, the shaft is threaded on to a mandrel. Using a fixed die below and a moving die above, the material is compressed. This results in a reduction in diameter and an axial widening of the material.  *Image: Hollow forging a shaft* When forging the flange, the straight flange starts to deform into a funnel-shape. To ensure that the shaft geometry can be machined from the forging geometry, large axial surcharges (allowances) are needed.  *Image: Funnel-shaping of the left-sided flange (forging simulation)* To reduce the surcharges, it is necessary to straighten the flange. This is achieved by compressing the shaft axially without a mandrel inside.  *Image: Straightening of the flange by axial upsetting the flange (forging simulation)*
AC	Lines 260-264

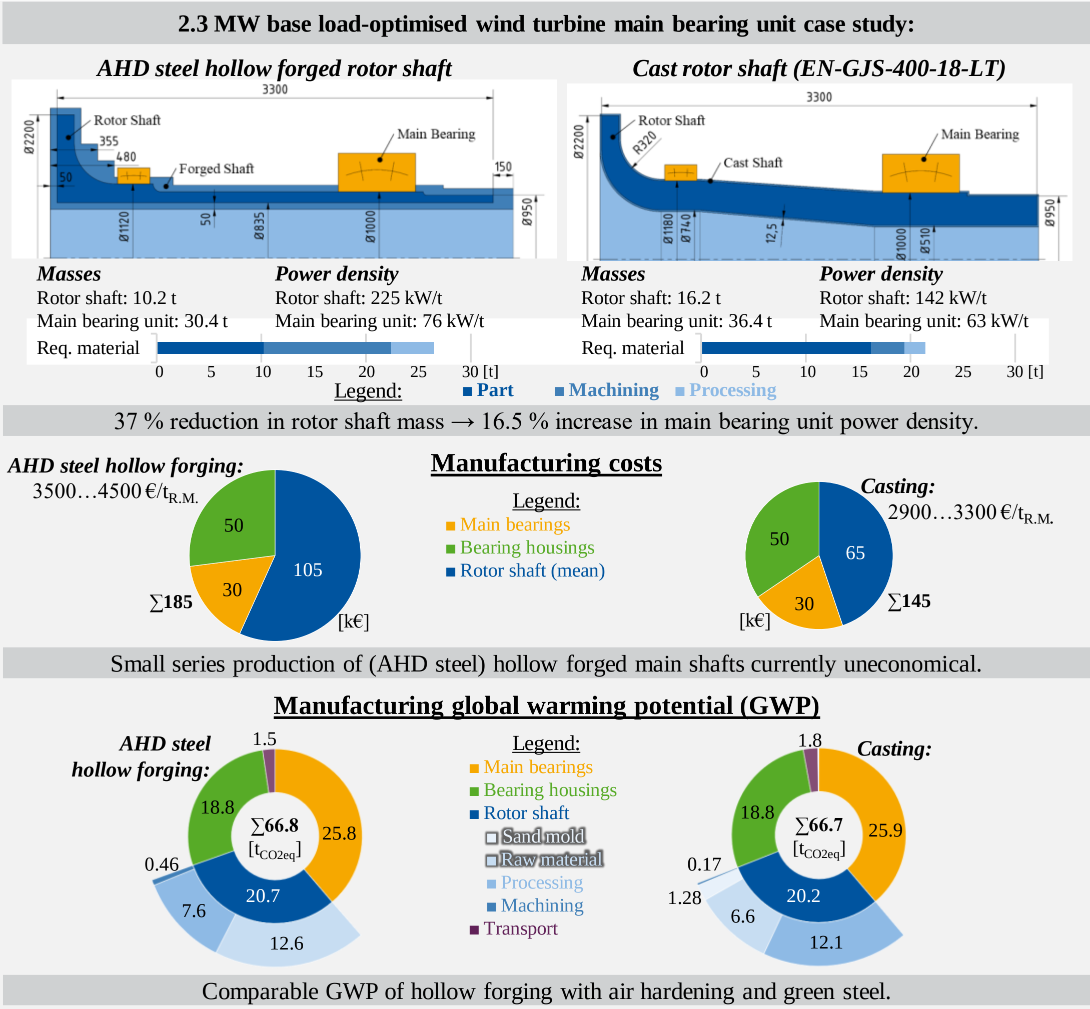
	By upsetting (compressing) the entire shaft in the axial direction between the forging steps, the flange area can be straightened, reducing the allowances required to compensate for the funnel-shaped collapsing flange areas and thus significantly reducing the masses in this area. ~~Axial upsetting between the stretching steps allows the flange area to be straightened in a targeted manner, reducing the required surcharges to compensate bending deformations and therefore lowering the masses in this area significantly.~~

4 Conclusions and Outlook

RC 10	Line 350 Here I am not clear on the percentages "total forging surcharges need to be reduced to around 50%". Does this literally mean in line 347 that instead of "160% in total compared to 32% for casting" it would have to be "50% in total compared to 32% for casting" to have similar costs, or would it be "80% in total compared to 32% for casting". I hope this question makes sense – it is a matter of discussing percentages of percentages. I think it is the former, thus when discussing the surcharge it has to be reduced from 160% to 50% for similar costs.
AR	The percentages are to be taken literally => The hollow forging surcharges are currently 160% of the final shaft mass and must be reduced to 50% of the final shaft mass (= -110%) to be evenly in costs compared to 32% for casting. The text was changed to avoid the confusion. Also added the "surcharges = allowance" point form RC 6, for those who directly read the conclusion.
AC	Lines 372-374 For forging to become cost comparable to casting, total forging surcharges need to be reduced from currently 160 % to around 50 % of the final shaft mass.
	Lines 366-367 This is due to the conservative forging surcharges (allowance) assumed (160 % in total compared to 32 % for casting).

RC 11	Lines 352 onward Maybe missing in the discussion of the GWP is that both shafts contribute less than 1/3 of the GWP of the total MBU. A larger portion actually comes from the bearings and housing. I wouldn't have necessarily expected this.
AR	The downwind main bearings are both oversized due to choosing them from a public bearing database. This adds bearing mass and therefore GWP for bearings and housings. So, it is more an around 1/3 than less than 1/3
AC	Lines 382-384 The main bearings and bearing housings currently make up more than two-thirds of the total MBU GWP. Using lighter, non-catalogue main bearings or switching to greener manufacturing processes therefore directly reduces GWP.

RC 12	Figure 6 In the middle figure, what does "Rotor shaft (lower)" and "Rotor shaft (spread)" mean? I don't believe I've seen this explained yet. Does this indicate the lower bounds and upper bounds for the shaft (i.e. the spread)?
AR	Adjustment of Figure 6 – Manufacturing costs for better understanding: - Removed cost range of rotor shaft and replaced them by mean value - Scaling diagrams such that the cheaper cast variant has a smaller circle (area ~ costs)
AC	New Figure 6 (repositioned to match layout)



Minor grammatical comments:

RC 13	Line 14: I think it would be clearer to say "…main bearing unit (MBU), consisting of the rotor shaft, main bearings, and bearing housings, are…"
AR	Accepted
AC	<u>Lines 13-16:</u> To ensure comparability between the hollow forged and cast rotor shaft, two predesigns of a main bearing unit (MBU), consisting of the~~,~~ rotor shaft, main bearings and~~,~~ bearing housings,~~)~~ are generated via a structural integrity assessment and calculation of the bearing lifetime according to ISO 76 / 281.

RC 14	<u>Line 18</u> I think it would be clearer to add "…the manufacturing GWP of hollow forging…"
AR	Accepted
AC	*See RC 2*

RC 15	<u>Line 172</u> Although it's October and near Halloween, "costumer" should be "customer" here.
AR	Typo corrected
AC	<u>Line 187</u> Transport costs to the customer ~~costumer~~ are excluded as these vary with the WT's location.

RC 16	<u>Line 181</u> Rather than "calculates to 2", is this more accurately "assumed to be 2"? Or was this truly "calculated" somehow?
AR	The 2 is based on the distribution of costs "For forged parts, Knight states that the material costs make up 50 % of the total manufacturing costs, with operating costs at 40 % and tooling costs (post processing) at 10 % (1992) " (old lines 174-175)

	If the material cost makes up 50% of the total costs, then 2x material costs ≈ total costs
AC	Line 197 The factor f_{TC} considers the relation between material costs (MC) and total costs (TC) and ~~calculates~~ derives to 2

RC 17	Line 230 Rather than “economically”, I think “economical” is better.
AR	Accepted
AC	Lines 246-248 Even when considering cost savings from a higher power density within the drivetrain, enabling thinner tower designs and reducing logistic costs, the AHD steel hollow forged rotor shaft is not ~~economically~~ economical yet.

RC 18	Line 258 A space is needed for “fromTable 6”.
AR	Accepted (New table results in number change)
AC	Lines 278-279 Using the raw material emission from ~~Table 6~~ Table 7, a specific emission value of 0.48 kgCO2eq/kg is set for AHD (green steel grade).

RC2

Clarifications needed

RC (1)	Line 53 DrivetrainSE does not consider hollow forged rotor shafts **The Claim in Question** In the paper, the authors state: *“Open source WT predesign tools like NREL’s DrivetrainSE (implemented into WISDEM) cannot consider hollow forged rotor shafts.”* This suggests that DrivetrainSE lacks the capability to model hollow forged shafts — but this is misleading or at least oversimplified. **What DrivetrainSE Can Actually Do** DrivetrainSE, as part of NREL’s WISDEM framework, does support modeling hollow shafts. Specifically: - Hollow Shaft Geometry: DrivetrainSE allows users to define outer and inner diameters of the main shaft, enabling the modeling of hollow geometries. - Mass and Inertia Calculations: It computes mass properties, stiffness and modulus based on these geometric inputs. - Material Properties: Users can specify different materials, including high-strength steels, though not necessarily AHD steel by default. **Evidence from cited ‘Hollas et al. (2024)’** In same authors’ earlier 2024 paper, they used DrivetrainSE to benchmark their custom MBU predesign tool. They acknowledged that DrivetrainSE could model hollow shafts, but not the specific manufacturing constraints of hollow forging – such as: - Maximum diameter jumps between shaft segments - Forging surcharges and material flow constraints - Air-hardening behavior of AHD steel **Clarifying the Distinction** So, the correct interpretation is: - DrivetrainSE can model hollow shafts geometrically and structurally. - It cannot model the manufacturing constraints and process-specific limitations of hollow forging, such as those relevant to AHD steel. This nuance is important. The present paper could have been clearer, avoiding confusion and improving technical accuracy and transparency, by stating: *“DrivetrainSE does not natively support the manufacturing constraints and material behavior specific to hollow forged AHD steel shafts.”*
AR	The sentence is oversimplified. Still DrivetrainSE is (currently) not suitable to predesign MBU with (air hardened / quench tempered) hollow forged rotor shafts. DrivetrainSE:

	- Main shaft diameter and thickness are user input values => User must ensure structural viability / iterate the geometry over multiple runs - Stress assessment is based on Frame3DD and compared the Mises stress with the material yield strength and a safety factor => The change of the yield strength over different material thicknesses is not included | notch factors – especially at the shaft flange are not included, as Frame3DD simplifies beams into segments with linear changing cross-sections - Limited bearing types and single dimension series (ratio height to width) => Limited optimization space (which also applies to public bearing catalogues) Cf. https://wisdem.readthedocs.io/en/master/wisdem/drivetrainse/index.html DriveSE (older version of DrivetrainSE): - Iteration of shaft cross-section until strength assessment is given - Main bearing limited to two scaled SRBs Cf. https://doi.org/10.2172/1215033 Requirement for own predesign tool: - Consideration of manufacturing constraints – e. g. diameter jumps, no conical segments - Consideration of manufacturing surcharges in strength assessment => dependency of yield strength from local wall thickness → *Line changed and sentence added to make unsuitability of DrivetrainSE clearer*
AC	Lines 53-57 Open source WT predesign tools like NREL's *DrivetrainSE* (implemented into *WISDEM*) (National Renewable Energy Laboratory, 2024; Guo et al., 2015) ~~cannot~~ are not suitable to consider hollow forged rotor shafts. While *DrivetrainSE* supports hollow shaft geometries, the tool does not consider manufacturing constraints, which differ between cast and hollow forged shafts and affect strength assessment.

RC (2)	Sec.3.2: Bearing usage inconsistency: CRB-TRB or SRBs? There seems to be a terminological inconsistency in the paper that could be considered an error or at least a point needing clarification. Comparison of the 2 Statements about Bearing usage Section 3.2, First Sentence: *"The original MBU comprises a cast rotor shaft with a mass of 16.2 t, a non-locating 2.1 t cylindrical roller bearing on the rotor side (upwind) and locating 0.9 t double-rowed tapered roller bearing on the gearbox side (downwind)."* This clearly specifies: CRB (non-locating, upwind), TRB (locating, downwind) Line 155: *"Both variants have similar bearing configurations, sharing the downwind spherical roller bearing and using a comparable spherical roller bearing upwind with a 60 mm inner diameter difference"* This contradicts the earlier statement by referring to SRBs on both sides. Technical Implication - CRBs and TRBs are fundamentally different from SRBs in geometry, load capacity, and misalignment tolerance — and the authors do have knowledge of this. - The choice of bearing type affects: Load distribution, Shaft deflection, Fatigue life, Assembly and alignment strategies If the design truly uses CRB and TRB, then referring to SRBs later is incorrect — unless the predesigned variants differ from the original configuration and this change was not clearly stated. Suggested Clarification It is recommended for the authors clarify: - Whether the bearing types were changed in the predesign variants. - If so, why SRBs were selected instead of CRB/TRB —especially given their different stiffness and misalignment behavior. - If not, then line 155 should be corrected to match the original bearing specification.
AR	Line 155: "*Both variants have similar bearing configurations, [...]*" refers to the two predesign variants, not the maxcap141-variant.

	Also, the focus of the study is comparing cast and hollow forged main shafts, using the maxcap141 as an example. The goal was therefore not designing a hollow forged shaft that fits into the existing maxcap141 but instead see how cast and hollow forged shafts differ in mass, power density, and GWP. To ensure compatibility between both, the study deliberately predesign a new cast variant and did not reuse the maxcap141 variant. For the maxcap141 predesign, shafts with SRBs are the power densest combination from all considered bearings (Schaeffler/SKF bearing catalogue). Given that the maxcap141 is a small wind turbine by modern standards, SRBs offer a great combination of load capacity and misalignment tolerance for their mass. For larger wind turbines, other bearing types might be more desirable, e.g. TRBs in an adjusted arrangement, even if they require pretensioning. That the maxcap141 (prototype turbine) uses a CRB and double row TRB is partly caused by the required use of standard, available bearings to keep costs low. The shaft / bearing housings was designed with those bearings as given… Regarding the technical implications, most of those are optimised after the predesign phase. Bearing properties like the load distribution were therefore not calculated/considered. The predesign was created to get an estimate what the best – power densest – shaft and bearing combination is for a given drivetrain (=> specifying the bearing diameter). The technical implication can be heavily influenced by the roller profiling, main bearing housing geometry, etc., which only have a small influence on the power density. They are therefore out of scope for the predesign and later design phased must optimise/define these. The shaft deflection/bearing misalignment is an edge case, as it is influenced by both the predesign and later design phases. The predesign therefore can consider a simplified shaft deflection by comparing the shaft deflection with limits for the allowable misalignment of different bearing types. This ensures that the shaft is made too thin while optimising its mass. => Sentence added before line to explain change in bearing type
AC	<u>Lines 168-170</u> Unlike the *maxcap141* variant, both predesign variants use spherical roller bearings (SRBs) as main bearings, as those offer a high load capacity and misalignment tolerance, enabling thinner shafts and therefore the highest power density of all catalogue bearings in this case.

Improvement Suggestions

RC	<u>1. Material Property Uncertainty</u> The fatigue behavior of AHD steel is extrapolated using FKM guidelines, which are not validated for this alloy (<u>line 105</u>). The paper acknowledges this but does not quantify the impact on reliability or safety margins.
AR	It's true that the FKM guideline doesn't apply to AHD steel giving a lack of data and different material properties (e. g. airhardening). Lab and industry samples of AHD alloys show, that the tensile strength is relatively independent of the wall thickness compared to quench tempering (QT) steels like 42CrMo4. Similarly, the alloy hardens under cyclic load, such that the fatigue strength increases under cyclic load unlike other steel types. Both effects are not reflected in the FKM guideline and the calculating the shafts utilization as if the AHD steel were a QT steel therefore results in unused safety margins. It's therefore assumed that the stress assessment is valid and overdimensiones the shaft.
AC	<u>Lines 113-114</u> Likewise, the cyclic hardening justifies that no additional safety margin is required when deriving fatigue strengths through the FKM-Guideline.

RC	<u>2. Lack of Reliability Analysis</u> The paper addresses structural integrity well, however there is no formal reliability-based design or probabilistic treatment of uncertainties (uncertainty quantification; e.g., in loads, material properties, forging tolerances). This limits confidence in the robustness of the design.
AR	The paper presents a predesign study. The presented hollow forged rotor shaft therefore must be refined in later design phases if it should be integrated into the *maxcap141* – e.g. a deformation analysis including the housings/machine frame, designing the bearing mounts. Comparing two predesigns (cast vs. hollow forged) allows load uncertainties to be neglected, as both predesigns use the exact same load cases. (Sidenote: the *maxcap141* shaft was designed considering multiple load cases from wind loads, assembly, …, form which the worst static and a damage equivalent dynamic load case was derived for the predesign – the loads are therefore also conservative).

	The forging surcharge are quite conservative to ensure that the final shaft geometry can be machined from the forged geometry. This results in worse material properties as the wall thickness is larger, cools slower and makes the shaft (currently) not economical. The material properties of the AHD alloy are currently based on lab tests/samples (e.g. tensile testing). To use the alloy in wind turbines, it must be certified (broadly tested) such that the material properties are validated. It is therefore believed that the shown mass reduction can be achieved using an AHD steel hollow forged shaft and through optimising the bearings even more. *See also Review 3 – RC 3*
AC	Lines 114-115 As the material properties are based on lab samples, ~~as~~ broad testing is required before the alloy is used in WTs to ensure reliability.

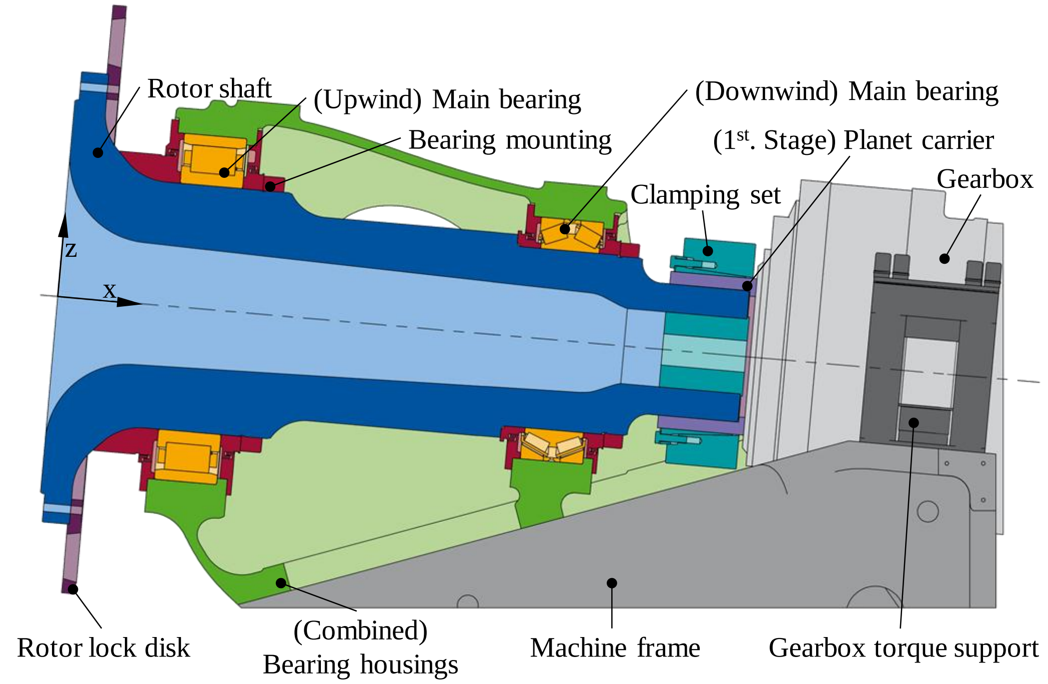
RC	3. Economic Viability Discussion The cost model is insightful but heavily reliant on assumed surcharges and outdated references (eg. Knight, 1992). A sensitivity analysis on cost drivers (e.g., alloy price, forging complexity) would strengthen the conclusions.
AR	As antitrust/cartel laws forbit cost reconciliation, it is hard to get any sort of literature for cost estimations. We therefore started with what was available in literature and used internal data to verify the cost estimations / fit the factors. Scaling effects (buying 1 or 100 shafts) and oversea manufacturing (e.g. China) were deliberately not included due to a lack of data. *To make it clearer that the KNIGHT reference was updated for the 2025 marked situation, a half-sentence is added (see AC).* A sensitivity analysis was not included, given the simple cost estimation formulas (mostly mass * factor) and breakdown percentages for material costs, operation costs (mostly energy) and post processing. As the forging costs scale with the forging mass / material required, a change in surcharges has the largest impact on costs. Using smaller, less conservative surcharges therefore is the best way to lower costs. *The current surcharges are the results of industry feedback and not simply assumed.* At least for hollow forging wind turbine rotor shafts, forging complexity is less of a concern as rotor shafts have a simple geometry. Unlike other forging parts, a rotor shaft does not have undercuts, and finer details must be machined form the forging geometry to ensure tolerances. The most complex part to forge is hence the flange transition, which can be either approximated with steps (as done here) or directly forged with a radius (depending on the forges preferences). The alloy mix influences the material price. As steel works manufacture material months in advance or have fixed deals with buyers, only long-term alloy element price changes effect material prices. How often an element is used in the alloys can have a larger effect than is actual price. Similarly, increasing energy prices makes steel more expensive. To avoid these uncertainties, we deliberately simplified the cost model. Predicting how the manufacturing cost will change given a 20% increase in nickel prices is impossible and outside this study's focus.
AC	Lines 152-153 Based on ~~industry~~ surcharges for small series production – which were provided by the industry –, the shaft geometry is extended by 150 mm axially and 50 mm radially, marked in Fig. 2
	Lines 190 – 192 Considering that the AHD steel is hollow forged and air hardens (no heat treatment needed), Knight's correlation is adjusted to Eq. (3) to model forging (F) and hollow forging (HF) shafts using internal and industry data:

RC	4. Digital Twin or Monitoring Integration Given the trend toward condition-based maintenance, the study could benefit from discussing how hollow forged shafts might affect monitoring strategies or digital twin integration.
AR	Hollow forging AHD steel rotor shafts as a technology currently has a technical readiness level (TRL) of 4, meaning that the feasibility was shown using simulations and lab-scale samples. Condition monitoring and digital twins are therefor for later (higher) TRLs and field tests / series production. For condition monitoring (CM) (and the subsequent maintenance), the rotor shaft is normally of less focus as main bearings or gearbox bearings/tooths have the higher failure risk. A failing rotor shaft would

	mean that either the design was unsuited (e. g. wrong load cases, underestimation of drivetrain deflection) or errors in manufacturing/the material. Condition monitoring cannot address design errors, while manufacturing errors are prevented using quality control measures (e. g. scanning the parts post forging for cracks) and certification of the material. Condition monitoring of the shaft should therefore not be necessary. Instead, the shaft can be – in theory – used to determine the rotor loads induced into the drive train using strain gauges. Knowing the rotor loads is a critical part in building a condition monitoring system. The problem is that it is hard to differentiate strain caused by e. g. bending vs. trust (cross talk between measured load components). Given the higher yield strength of steel versus cast iron, a hollow forged shaft should make strain measurements easier. Furthermore, ring creep must be considered in the MBU design. A thinner hollow forged steel shaft increases the risk of structure induced ring creep between the rotor shaft and main bearing inner ring compared to a cast shaft. This in turn might require a condition monitoring system to measure the ring creep in operation and possible predict bearing failures. For digital twins, it is important to distinguish between manufacturing and operation of the shaft. In operation, the shaft is not expected to see wear or fatigue damage in its lifetime and is therefore of lesser focus in a digital twin. A digital twin of the hollow forged shaft during forging on the other hand might help reduce the manufacturing surcharges and there make the shaft cheaper. Having a good understanding of the material flow and cooling during/post forging helps to better predict the material properties of the shaft. This would than allow maximizing the material utilization in the strength assessment and reduced the shaft mass/surcharges. Furthermore, using a digital twin with high process understanding, an adjustment of forging steps during manufacturing might become possible to e. g. account for changes in material flow or optimize reheating steps. *As digital twins and condition monitoring are outside the study focus and TRL, no changes will be made.*
AC	*None*

Review 3 (Minor Revisions)

RC 1	Figure 1: I appreciate the changes made to the figure; however (it's very minor and sorry for missing it in the first review), I believe "(1st Stage) Planet Carrier" should point to the purple-colored element rather than the blue-colored Rotor shaft and the "Clamping set" should point to the aqua-colored element. Right?
AR	Yes, those two are switched => Labelling updated (New Figure also inserted for Review 1 – RC 5
AC	Figure 1 (new)



RC 2	Line 88 (new Version): Also very minor, but rather than the simple addition of "…surface surcharge (allowance)…" I think it would be beneficial to add the longer explanation in the author's response here "…surface surcharge (i.e. added material for forging/casting to ensure that the final geometry can be machined within the required tolerances from the forged/cast geometry)…".
AR	As allowance is a synonym for surcharges, the old sentence was kept. Instead, a new line is added with the suggested explination.
AC	Line 89-92 Sand casting requires a surface surcharge (allowance) of up to 50 mm, approximately 20 % of the shaft mass, and 10 % additional material for sprue and other material loses (Weiß, R., 2024). This ensures that the final geometry can be machined to the required tolerances from the cast/forged geometry.

RC 3	Line 112 (new Version): Small typo in the new text here related to "As" and "…as" in the same sentence. I believe it should be "As the material properties are based on lab samples, broad testing is required…"
AR	Error corrected
AC	Line 114-115: As the material properties are based on lab samples, ~~as~~ broad testing is required before the alloy is used in WTs to ensure reliability.

Other changes

Table 3-10: Change of table numbering given the additional Table 3

Line 38: cross section instead of cross-section for consistent spelling

Line 94: Figure 1 description: *maxcap141* in italic for consistent spelling

Line 140: *WISDEM* / *DrivetrainSE* in italic to match other proper nouns

Line 241: End of sentence changed from period (.) to colon (:), as table follows immediately

Line 352-359: Block spacing removed

Line 470: Inserted missing references author:

James Durrans GmbH: Aufkohlungsmittel, www.durransgroup.com/de/produkte/aufkohlungsmittel, 2025.

Line 496: Inserted missing references author:

Saarstahl AG: Saarstahl - 42CrMo4 - 42CrMoS4: Werkstoff-Datenblatt, www.saarstahl.com/app/uploads/2024/03/20160318114440-42CrMo4-42CrMoS4-.pdf, last access: 15 January 2025, 2024.