Joule

Design of Hybrid Wind Turbine with Embedded Mechanical Storage providing Dispatch Capability

--Manuscript Draft--

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Abstract:	Wind power is one of the lowest cost, fastest growing options to reduce CO2 emissions globally. Variability is the major barrier for its comprehensive replacement of fossil alternatives. Despite intensive efforts, battery storage remains expensive as a means to mitigate the variability. Here, we propose a novel hybrid wind turbine design with several mechanical transmission and mechanical storage add-ons. The modified system is capable of capturing kinetic energy otherwise wasted at high wind speed, releasing it at lower wind speed. It provides for higher efficiency, enabling also critical dispatch capabilities missing with conventional systems. Tested based on real-world data, we show that the reconfigured design can increase energy yields by ~20% for wind-rich areas in both the US and China, enhance revenue by 25%-100% for different US power markets, while realizing a 63% reduction in capacity required to accommodate a specific CO2 reduction target for wind-rich regions in China.
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	systems

HARVARD
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Dear Editor,

Thanks for the extensive efforts devoted to evaluating our manuscript. We do agree that technical details are important for a feasible real-world application, which we highly value and have devoted significant effort to. Part of the work dated back to the first patent (WO2017/117414) from one of our coauthors since 2015. However, these technical details were not included as we try to improve the readability for general audience (as should be for such high-level journals), leading to a host of questions regarding the practicality and technical details from reviewers. Now we have provided a 40 page long supplementary information, providing analyses from mechanical structure, to rotation speed and torque calculations, to enhancement of drive train, tower and foundation, to the pressure, force, and efficiency modeling, to detailed cost breakdown. With all these analyses, we have shown that strengthen of drive train, tower and foundation did not incurred significant increase in costs. These modifications will not change the cost effectiveness or hamper the. Discussions on key challenges for real world implementations is presented at the end of the paper.

We also clarified the misunderstanding from reviwer #3 and cross-talk referee that the extra energy harvested is the major benefit of the turbine. In fact, the primary benefit of this design is to provide dispatchability rather than providing additional energy. We have demonstrated that, with the proposed hybrid wind turbine, the revenue in electricity market has doubled for California and CO_2 abatement cost could cut by half in Inner Mongolia. We have modified the wording on this part to avoid confusion. Also, we provided a quantitative case study to demonstrate that for wind rich locations in China, the energy spillage constitutes as high as 34% of the captured energy in these places.

A 30-page response is provided to address the detailed questions from all reviewers. With all these explanations, we strongly believe that the proposed hybrid turbine design provides a major realistic opportunity to decarbonize the energy system.

Sincerely,

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CHANGES INCORPORATED

We would like to thank the editor and reviewers for the helpful comments and for the thorough review of our paper.

Summary of Editor's comments to the Author:

[original comments] As you will see, while referees #1 and #2 were broadly positive about your design and analysis, referee #3 was much more concerned, feeling this work didn't meet Joule's demanding requirement for reporting a clear pathway to real-world energy impact.

My editorial team discussed your manuscript and the reports carefully. We don't blindly follow referee recommendations or make decisions "by algorithm", but try to weigh up relevant evidence to arrive at a reflective decision. Here, we had shared some of referee #3's concerns, as, while Joule is very much receptive to innovative and disruptive new ideas, they do need to be appropriately-grounded in real world considerations.

So for the fairest process, we decided to initiate a process we sometimes use when we have conflicting initial reports, and we sent your manuscript and the three reports for further "cross-talk" evaluation by an expert with significant experience of wind power in both academic research, bigger analysis, and industry settings. We have now received these further comments, which are also copied below (along with an attachment this referee provided).

[comments after the rebuttal] More generally - I appreciate your constructive engagement with the referee reports – we understand that the peer-review process is underpinned by editors and reviewers making subjective decisions, and that the right decision isn't always reached (or indeed that what is the "right" decision is hard to define). As such, we welcome author feedback – this makes us think carefully about our decision making process (both for a specific manuscript, and more generally going forwards), and acts as a "check and balance" in complex cases.

After discussing your rebuttal carefully with my Joule editorial team – we are somewhat torn. The major difference between you and the negative reviewer input is around whether your new design has a pathway to real-world energy impact (which is something Joule values), or whether it is of more theoretical interest. I recognise you feel you have addressed the key *concerns here, so we feel it would be fairest to approach a further independent expert reviewer for final adjudication.*

Replies to the editor:

- Thanks for the extensive efforts devoted to evaluating our manuscript. We do agree that technical details are important for a feasible real-world application, which we highly value and have devoted significant effort to. However, we think there are some major misunderstandings from reviewer #3 and the cross-talk referee. This manuscript is originally organized to target the general audience (as should be for such high-level journals). Important pieces of information are missing for the review regarding the detailed torque and weight analysis, which leads to biased judgments. Based on this, we provide extensive evidence responding to the ungrounded criticism from the reviewer 3 and cross-talk referee. The supplementary has now been extended to over 40 pages, covering all grounded from detailed mechanical structures, to torque, weight and cost analysis, to internal pressure, control logic and efficiency analyses of mechanical add-ons, to system analyses for dispatching, bidding and unit commandment models. The misunderstandings are clarified with point-to-point responses followed. Several explanations are listed below.

- Reviewer #3 and the cross-talk referee's major criticism is that we lack a description of detailed mechanical structure, including the redesign on the turbine, which leads to the question of the practicality of the proposed hybrid wind turbine. In fact, our team members had conducted a detailed analysis of the mechanical structure, as well as subsequent analysis for internal torque, pressure, and weight. Part of the work is dated back to the first patent (WO2017/117414) from one of our coauthors since 2015. Some detailed analysis associated with internal torque, pressure, and weight are too complicated for general readership and was thus not included for considerations of the readability of the paper. We have now incorporated the missing part for mechanical pressure, torque, weight, and in the revised supplementary text. For example, as the high-pressure air tank is placed on the ground, the weight increase accounts for only 10% of turbine top mass and about 1% of the total mass, which should not cast a big concern for the proposed hybrid turbine. Changes in torque and reinforcement of the turbine structure is also quantified, as detailed in the SI and responses.

- Another major argument is that wind speed is mainly within the range of 3-11 m/s, and there is no point in capturing such little additional energy with complicated turbine design. We have examined over 2879 locations in China. For some of the locations, it is indeed the case that wind speed is mostly within the range of 3-11 m/s. However, for wind-rich locations in, for example, Inner Mongolia, the wind speed is frequently higher than 11m/s. Since the energy is related to the cube of the wind speed, the energy spillage constitutes as high as 34% of the captured energy in these places. We note that such wind reach regions in Northern China, Northwest China, and Northeast China, accounting for over 70% of the current wind installation in China. We have clarified this point in the updated supplementary information.

- Moreover, the primary benefit of this design is to provide dispatchability rather than providing additional energy. The imbedded mechanical storage can function also at lower wind speeds to avoid curtailments or maximize the market revenue. As a result, installing 23GW of hybrid wind turbines can achieve the same CO_2 reduction level when installing 60GW of traditional wind turbines(illustrated in fig. 3a). The overall benefit gain in the electricity market is much higher. The result has shown that the revenue in the electricity market has doubled for California with the proposed hybrid wind turbine, the most important state in the U.S. in terms of decarbonization. In fact, this turbine can replace in part the combination of traditional turbine and storage, which is the true benefit of the proposed turbine design. Reviewer #3 and the cross-talk referee might be very knowledgeable for the single wind turbine but did not see the true benefit of the proposed design. We have emphasized this in the updated main text as well as the supplementary information.

- In responding to comments from reviewers 1# and 2# , we have included detailed description of electricity market bidding model in US and power system dispatch model of western Inner Mongolia. The challenges for real world implementation has been discussed at the end of the updated manuscript. We noted that rigorous engineering and testing should be carried out, including real-world capability, system reliability, wear and tear remedy, durability and extreme condition performance. Government R&D funding will be required to support the initial development, as it is expected to be more costly compared with marginal improvements of conventional turbines. However, the amount of funding required should be orders of magnitude lower than those devoted to research and piloting of grid scale battery technologies. The importance of incorporating the hybrid wind turbine into the local energy policy framework is addressed also.

- The detailed responses are given below. The manuscript is now revised extensively to strike a better balance of getting the big picture idea cross to general readership in the main text, and elaborating the engineering details in the supplementary text. With all changes and clarifications indicated above, we strongly believe that the proposed hybrid turbine design provides a major opportunity to decarbonize the energy system.

Replies to the reviews:

Reviewer #1:

This article is excellent and with important academic and applied value. It proposes a novel hybrid wind turbine design with several mechanical transmission and mechanical storage add-ons, which could provide for higher efficiency, enabling, in addition, critical dispatch capabilities missing with conventional systems. In addition, the modified system is capable of capturing kinetic energy otherwise wasted at high wind speed, releasing it at lower wind speed. The new wind turbine design offers a promising cost-effective approach for rapid de-carbonization of energy systems globally. However, before publishing this article in this journal some concerns need to be addressed.

Comments:

1) In the part of Results, several subtitles should be added to clarify the main content of this article. As I know, it contains several points: (a) the detailed structure of the novel hybrid wind turbine (maybe this section should be listed separated but not in the section of Results); (b) the contributing of the proposed turbine, i.e., inverse the total yield of electricity, improve revenue for wind producers in US electricity markets, and mitigate the curtailment issue in China; (c) the incremental costs.

Reply:

- Thanks for positive comments on the paper. The thoughtful suggestion on subtitles do increase the readability of the paper. We have incorporated the subtitles in the revised manuscript, as colored in blue.

2) One of the important contributions of this turbine is it could improve the revenue of the producers. Meanwhile, the paper quantifies the benefits of the new wind turbine in actual US power markets, how these be simulated, the corresponding method or references should be elaborated in this article or its supplementary materials.

Reply:

- Thanks for the comment. The description of this part is simplified in the initial submission of the manuscript considering the readability for general readership. We have now elaborated the model and data for the market simulation in section S7 of the Supplementary Text.
- First, we formulate the internal power flow model of the hybrid WT, as indicated in Equation (16)-(22). Such a model provides power and energy flow, as illustrated in Figure S12. Then, we use the internal power flow model to formulate the electricity generation maximization model (23). The model (23) helps to investigate the extra power the hybrid WT could bring to the owner of wind farms and is applied to over 6000 locations in both China and the U.S. Finally, we formulate the optimal scheduling model to maximize the revenue of wind farms in the wholesale market, i.e., Model (24). Such a model is applied to six power markets in the US., and the description of the model and data source are also provided in this section.

- We note that we only consider the energy market in our analysis. However, a major source of income is from the ancillary service market. Thus the revenue presented is relatively conservative. We have added the relevant discussion in the updated manuscript.

3) From the authors' states, it can be notably found that the proposed hybrid wind turbine designed in this paper contains several advantages compared with the traditional wind turbine utilized in the wind farm currently. However, the drawbacks, in other words, the difficulties for application and promotion of the designed turbine need to be discussed in the last section.

Reply:

- Thanks for the critical suggestions. The major disadvantage is increased cost when incorporating the CVT, VDM, mechanical storage, and reinforced turbine shaft, tower and foundation. However, the cost increase is outweighed by the significant benefit provided.
- The difficulties for application and promotion of the designed turbine fall into two aspects:
    a) Reliability, testing, and certification: Rigorous engineering test should be conducted from conceptual prototype to type-and-component certification to ensure that it can survive and work as expected in the harsh environment like other wind turbines do. This requires the considerate designs on the real-world capability, system reliability, performance assurance, wear and tear remedy, etc. Since this technology would employ technologies which is developed initially in other industry, i.e., automobile industry and oil and gas industries, the development of this hybrid wind turbine needs a close cooperation and collaboration with other industries. New criteria of certification may need to be developed or amended to cover all components used in the hybrid wind turbine. Government R&D funding is required to support the initial developments, as it is expected to be more costly compared with marginal improvements of conventional turbines. However, the amount of funding required should be orders of magnitude lower than those devoted to research and piloting of grid scale battery technologies.
    b) Policy enforcement: Incorporating the hybrid wind turbine into the local energy policy framework is equally important. Investments of wind power has been restricted in wind-rich, northern regions in China because of the curtailment issue, and the growth rate dropped to less than 3% in north western and north eastern regions. China should exempt such restriction for the hybrid wind turbine given its enhanced dispatchability. In US, the primary income of grid level storage system sourced from frequency regulation markets. The hybrid wind turbine, with the inherent storage capability, should be allowed to participate the ancillary service markets as well as the capacity market to further maximize the profits. Special quota for storage has been established in part of US and China, and hybrid wind turbine should be also eligible for these subsidy.
- We have incorporated the above discussion in the discussion section of the updated manuscript. Thanks again for the suggestions.

Reviewer #2:

This paper proposed an innovative energy solution to replace the fossil units. The idea is original, and the impact could be substantial. The variability of the wind power output has been the primary obstacle for it utilization at very high penetration of renewables. This paper provides a smart design of the wind turbine, offering a potential to make the wind turbine dispatchable, capturing more energy with less overall costs. The results are very comprehensive, covering both China and US, considering energy production, electricity market and power system dispatch. However, some of the analytical part in the SI is limited maybe because of the page limit. These parts should be expanded. Several detailed suggestions:

Comments:

1) The description of Western Inner Mongolia System should be enhanced, including the generation mix of WIM system, power demand information, including peak capacity, wind power generation profile.

Reply:

- Thanks for the comment. West Inner Mongolia (WIM) is a representative example of the three northern regions where China's wind power potentials are the greatest. The detailed description of WIM System has now been supplemented in Section S8 of the supplementary text. The key points associated with the generation mix, power demand, and wind power generation profile of WIM are listed as follows.
- The generation mix of WIM is mainly composed of combined heat and power plants (CHP) and wind power [R5, R6]. The CHP capacity of WIM has increased from 4.5GW (2003) to 26.1 GW (2013) and is projected to reach 33.8GW in 2020. The wind power capacity in WIM increased from 0.04 GW (2004) to 10.8 5GW (2013) and is predicted to reach 40 GW in 2020, respectively. Moreover, WIM has a capacity of 0.3GW gas plant and 1.17GW hydropower plant [R5, R6]. In our simulation, we ignored the gas plant and hydropower plant due to their little share in the whole generation mix. In terms of power demand, the peak-load power demand is 26.012GW, and the electricity consumption is projected as 211.75 TWh in 2020 according to the load forecast results [R5]. The wind power generation profile of traditional WT and the proposed hybrid WT are illustrated in Fig.4A in the manuscript.

1) The model for optimal bidding the market price should be elaborated.

Reply:

- Thanks for the comment. The description of this part is simplified in the initial submission of the manuscript considering the readability of general readership. We have now elaborated the model and data for the market simulation in section S7 of the Supplementary Text.
- First, we formulate the internal power flow model of the hybrid WT, as indicated in Equation (16)-(22). Such a model provides power and energy flow, as illustrated in Figure S12. Then, we use the internal power flow model to formulate the electricity generation maximization model (23). The model (23) helps to investigate the extra power the hybrid WT could bring to the owner of wind farms and is applied to over 6000 locations in both China and the U.S.

Finally, we formulate the optimal scheduling model to maximize the revenue of wind farms in the wholesale market, i.e., Model (24). Such a model is applied to six power markets in the U.S., and the description of the model and data source are also provided in this section.

- We note that we only consider the energy market in our analysis. However, a major source of income is from the ancillary service market. Thus the revenue presented is relatively conservative. We have added the relevant discussion in the updated manuscript.

2) The paper is very well written. However, the sentence starting with "The detailed reference nodal price selection method" in the SI is incorrect. Please revise.

Reply:

- Thanks for spotting the mistake. We've revised the sentence and provided the missing reference. The revision is colored blue in the updated SI.

Reviewer #3:

Overall Comments

The paper makes a very interesting conjecture about trying to capture the 'wasted energy' which occurs when a wind turbine is operating at a fixed electrical output with winds ranging between its rated speed (authors state 14 m/s (31 mph), but use turbines with 11 and 12 m/s rated speeds) and its cut out speed (often 25 m/s or 56 mph). Mechanical systems (CVT, VDM, and TES) are described as being able to make energy conversion from mechanical/electrical energy to compressed air augmented with thermal storage. The excess energy harvested would be stored for use when wind speeds are below rated power to augment turbine electricity production during these lower wind speed periods thereby creating a more consistent energy delivery profile for each turbine. The CVT and VDM systems identified to do this are taken from the automobile industry with simple rated power and cost scaling to interface seamlessly with 1.5 and 2.5 MW wind turbines.

There are theoretical energy calculations in the Supplemental Information that lay out boundary conditions amongst a host of variables which are subsequently used for economic modeling. However, there has not really been any engineering modeling with component design specifications, operational parameters and limits, etc. The proposed system configuration would require re-design of virtually every turbine component and possibly the tower. This level of alterations to wind turbine system hardware would likely require new laboratory testing leading to field testing leading to re-certification by IEEE. All of which is non-trivial in scope, effort, time and cost. It cannot be predicted from here (not enough information across all items mentioned above), but the additional re-design, testing and certification costs of the proposed turbine component additions may ultimately erode some or all of the proposed additional revenue potential. As such, the extensive effort into the

economic modeling and economic potential (approximately half or more of the paper) appear significantly premature. It is highly recommended that engineering rigor be applied before proposing investment-driving economic conclusions.

Reply:

- Thanks for acknowledging our positive contributions and raising questions on the engineering details of the turbine redesign. Our team members have conducted a detailed analysis of the mechanical structure, as well as subsequent analysis for internal torque, pressure, and weight. Part of the work dated back to our first patent (WO2017/117414) since 2015. However, this manuscript is originally organized to target the general readership (as should be for such high-level journals). Some detailed analysis associated with internal torque, pressure, and weight are too complicated for general readership and was thus not included.
- We have incorporated the missing parts (detailed structure, internal force, changes in rotation speed and torque, changes in weight, structural adaptations) in the updated supplementary text. As indicated in the revised supplementary text, these analyses lead to the quantitative analysis on how to strengthen shaft and tower. In addition, the detailed control model and unit commitment model to dispatching the hybrid wind turbine is also presented in detail. Responses to detailed questions associated with turbine redesign are given below.

[Part I] Detailed comments about specific statements in the paper

Page # Paper text

Comments

1) p. 3 Summary Tested based on real-world data,

There was no testing, it was modeling using modeled MERRA-2 data.

Reply:

- We have modified the statement on this. The data incorporated are mainly two types: 1) Electricity prices in different ISOs in the U.S. and operational data for Inner Mongolia Power System in China are based on actual data. 2) Wind speed data for sample locations in China and U.S. are derived from MERRA-2 assimilated meteorology data. “Real-world data” mainly refers to the former.
- Given that this paper analyzed about 2879 locations in China and 2636 locations in the U.S., incorporating the measured wind speed data are not feasible at such a scale. The MERRA-2 data has the best data source available in this case, not only because of the wide geographical coverage, but also the temporal resolution and duration. Incorporating such data source allows us to consider the temporal variations on weekly, daily and seasonal scales for all possible locations. It has been applied in a variety of top publications. The temporal variation of wind speed from MERRA-2 has been compared with actual data in the U.S. and in China with satisfactory correlations in the previous literature [R8, R9, R29]. Although we admit that the MERRA-2 has a relatively weaker correlation in EUROP given the more complicated land-sea interaction.

2) p. 5 When the wind speed is higher than the rated speed of the turbine, the generator reaches its capacity limit (rated capacity) and pitch control is activated to reduce the fraction

of energy captured by the blades, resulting in under-utilization of available wind kinetic energy. To resolve this dilemma, we propose a hybrid design capable of storing kinetic energy otherwise wasted at higher wind speeds, reusing this source at lower wind speeds taking advantage of generator capacity that would be idled otherwise.

Pitch control of the rotor lowers torque translated to the lower speed shaft thru to gearbox to high speed shaft to generator. To capture the wasted wind energy would require not pitching the rotor and increasing the applied torque resulting in wear and tear on all components mentioned, increasing O&M costs, and requiring significant re-design of all of these components as they have been designed with the constraint of the load-reducing benefits of the pitch mechanism working.

Reply:

- The structural redesign due to the increase in torque and weight has been taken into consideration since our first patent (WO2017/117414) in 2015 [R10]. The previous manuscript, considering the readability for a general readership, only provided final results for incremental costs (reflecting the changes in torque, weight, etc.) We have provided a detailed analysis of the necessitated redesign to recycle the wasted wind kinetic energy through analyzing the toque balance of the shaft, the mass variations of such a redesign, and its impacts in cost in the revised supplementary text. The key results associated with the change of control mechanism, O&M cost, and redesign are listed as follows.
- The changes in torque and rotation speed for hybrid wind turbine and typical conventional wind turbine is summarized in Fig.R1 below. As indicated, the operational region of the hybrid WT is divided into three segments for different operational schemes by four wind speed points, including cut-in speed, electrical rated speed, structural rated speed, and cut-out speed. The conventional WT adopts maximum power point tracking (MPPT) strategy in Region I, and uses pitch control in both Region II and Region III. While for the hybrid WT, it follows MPPT control in both Region I and Region II, and adopts pitch control in Region III. The reason for using MPPT control in Region II is to capture otherwise wasted kinetic energy through the coordinated control of CVT and VDM. It should be noted that the change of control method in Region 2 can be easily implemented through the modification of parameter settings of control software. The more detailed explanation for the modification on mechanical control can refer to section 2 of the supplementary text.
- As indicated, the rotation speed of hybrid WT is increased up to 2.69 rad/s in Region II and III. Wind blades for conventional turbines are designed in general to survive under 70m/s wind conditions [R11] for conventional turbines. Thus, the increase in the rotation speed does not pose a threat to the wind blade of the proposed hybrid WT, and the blade mass stays unchanged. The maximum torque on the shaft would increase by 66.86% at higher wind speeds, and correspondingly the lower speed shaft (attached to the rotor) requires a major reinforcement. We note that the higher speed shaft (used to connect to the generator) remains unchanged as the rating of the electrical generator is constant. Our analysis indicates that the introduction of CVT and VDM, as well as the increased weight of lower speed shaft accounts for 10.30%~15.49% of the mass of turbine top (including rotor and generator), the increased top mass only accounts for 1.04%~1.60% of the weight of the turbine. The more detailed

analysis of the impact of weight distribution and enforcement of tower and foundations are given in section S3 of the supplementary text.

- Regarding the O&M cost, since the reliability and longevity of CVT and VDM reliability based on previous storage cases, including the Huntorf plant in German and McIntosh plant in the U.S., have been built in 1978 and 1991 respectively. These two plants are still working well to support peak-shaving and integration of renewable energy, and their O&M costs are small. Moreover, as indicated in Table S3 in the supplementary text, and O&M cost for conventional wind turbine only accounts for a small share of the total. The cost increment ratio of hybrid WT over conventional WT imposed by CVT and VDM are 2%~4% and 5%~6%, respectively. As a result, the increased O&M cost associated with CVT and VDM is not significant.

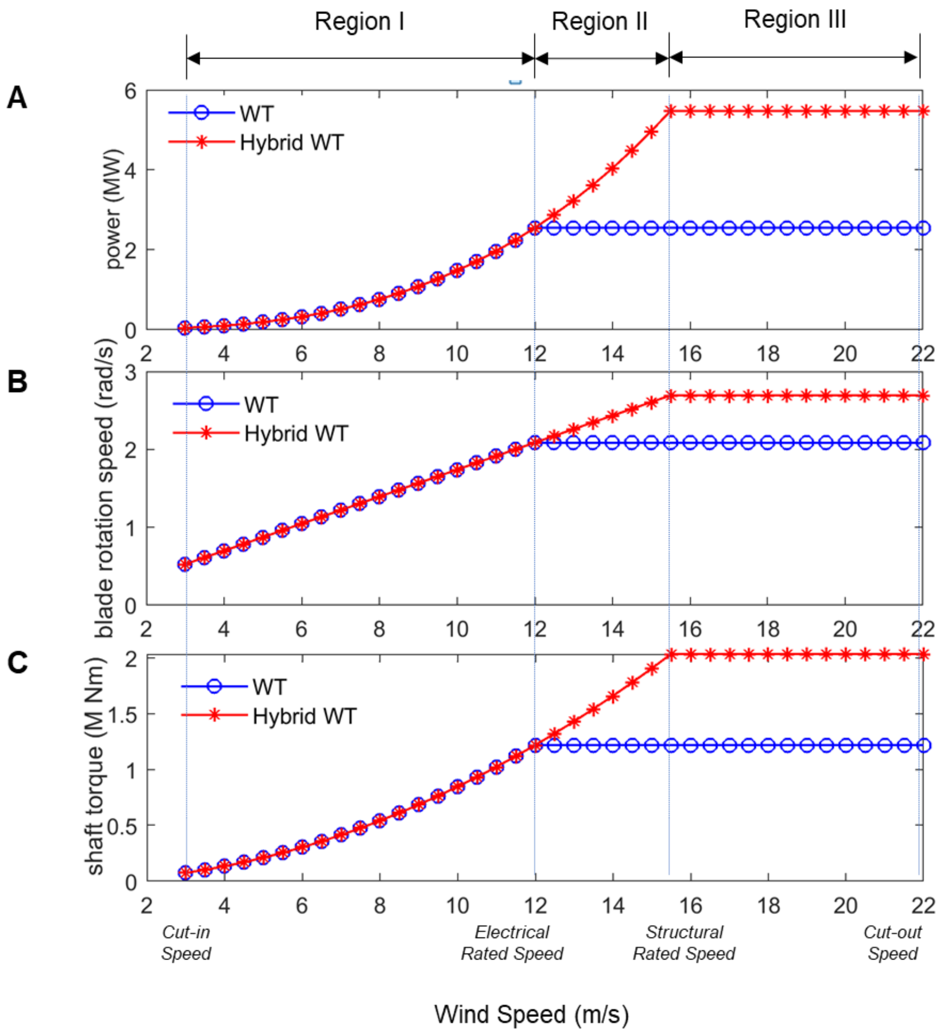


Figure R1. Comparison of blade rotation of conventional WT and the proposed hybrid WT with 2.5MW rated power. (A) Power curves of WT and hybrid WT. (B) Rotation speed curves of WT and hybrid WT. (C) Shaft torque curves of WT and hybrid WT.

3) On p. 9 of the Supplemental Information, the authors do cite increased cost shaft torque and

shear stress and the necessity of increasing shaft diameter at an additional $/kg cost.

There is no accounting for resultant increased power train system, nacelle, and tower re-design costs, increased wear and tear throughout the system resulting in increased O&M costs.

Reply:

- The change in weight, torque and the strength of the tower and foundation, while introducing the mechanical add-ons, have been considered in detail in the analysis. We have provided a detailed analysis of the mass variations on the drive train, nacelle, and tower caused by such a redesign in section S3 of the revised supplementary text.
  a) Related control method and changes in torque and speed on the shaft has been presented above in Fig.R1. Our investigations indicate that the rotation speed is increased up to 2.69 rad/s at higher wind speeds, and the maximum torque on the shaft would increase by 66.86% at higher wind speeds.
  b) The enforcement of power train due to changes in torque has been detailed in sections S2 and S3. The lower speed shaft needs to be strengthened to resist the increase of torque. According to relationship between force and mass, the lower speed shaft needs a 69.91% increase in weight. However, the higher speed shaft remains the same as the rating of generator is the same.
  c) Breakdown of mass for different components for conventional wind turbine, and changes in mass due to the mechanical add-ons are summarized in detail in section S3. The analysis on the mass variations of the hybrid WT indicates that the introduction of CVT and VDM, as well as the increased weight of lower speed shaft accounts for 10.30%~15.49% of the mass of turbine top (including rotor and generator), and the increased top mass only accounts for 1.04%~1.60% of the total weight of the turbine. Such mass increase leads to an about in 10.59%~15.86% increase of tower mass, and strengthen of the foundation by 10.56%~15.82%.
  d) Detailed breakdown of capital cost for the hybrid WT is presented in section S9. Compared to the conventional WT with the same power capacity, the cost of the hybrid WT is increased by 11.49%~15.19%. In particular, the cost increases due to the strengthening of tower and foundation contribute to 2.04%~3.01% of the total costs, as these parts are relatively less expansive compared with rotors and generators.
  e) Besides, the increased O&M costs can be easily estimated with the mass variation by using the scaling relationship between mass and cost in the NREL cost model [R12] and integrated into the optimal sizing procedures of such hybrid wind turbines. More details on the cost breakdown analysis can refer to section 9 of the supplementary text.
- In a nutshell, we do have analyzed the detailed consequences for incorporating the mechanical add-ons into the wind turbine. Quantitative analysis of changes in torque, resultant changes in power train, the enforcement of tower and foundations have all been conducted. Results have shown that these parts only attributes 2.04%~3.01% of increase of the total costs, and was not a primary challenge for the implementation of hybrid wind turbine.

3) p. 6 Diagram D: Continuous variable transmission (CTM)

The insertion of the CTM involves a major redesign of the entire power conversion system as it will impact every design element to siphon off power with this device.

Reply:

- The introduction of CVT and VDM did increase the torque and weight of the turbine. As noted above, detailed analyses for torque changes, consequent enforcement of drive train, increase in weight, and addition in total costs are presented in sections 2, 3 and 9 of the supplementary text. Our investigations indicate that the rotation speed is increased up to 2.69 rad/s at higher wind speeds, and the maximum torque on the shaft would increase by 66.86% at higher wind speeds, as indicated in Fig.R1. The lower speed shaft needs a major reinforcement, as indicated above. The introduction of CVT and VDM, as well as the increased weight of lower speed shaft accounts for only 1.04%~1.60% of the total weight of the turbine, leading to 10%-15% of strengthen of tower and foundations. The increase in weight is relatively minor as the heaviest part- air storage tank is placed on the ground. These adaptation incurred 2.04%~3.01% increase of the total costs, as tower and foundations are relatively less expensive parts compared with rotor and generator.
- In sum, the redesign of the tower has been conducted based on quantitative analyses, and the results fully support the feasibility of real world implementation of the hybrid wind turbine.

4) p. 7 With an increment of 5% and 10% in blade lengths of the hybrid turbine, capacity factors could be increased by 20%~37%.

An increase in blade length increases the capacity factor (CF) in the turbines mentioned. For the increase in CF cited to have any validity, it should be compared to the resultant increased CF in the conventional turbine with blades lengths increased by 5 and 10%. Only the net difference can be claimed as an advantage of this system.

Reply:

- Thanks for pointing out the ambiguity of this part. The main text did adopt the exact same blade length for comparison. The statement above referred to the sensitivity analysis presented in Fig. S9 in the revised supplementary text, and the results we provided are compared with the conventional turbine with blades lengths increased by 5% and 10%.
- We have clarified this part in the updated manuscript, as colored in blue.

5) p.8-9 At night when the wind is strong and power demand is low, the wholesale price of electricity can decline to zero or even become negative (15). Revenue for wind producers is limited over these time periods. The new design, on the other hand, allows for adjustment of electricity output in response to price fluctuations, since the power output and wind speed are largely decoupled.

This appears to be a misstatement of how the system operates and the savings associated with storing wasted wind energy. The above rated power periods, the turbine will still be producing its maximum rated power which will have little value to the grid. It is only the excess, if stored and provided later that will have value. Most of the power will still have to be sold to the grid *when generated even if at low prices*

Reply:

- There are some **major misunderstandings** in the dispatchability provided by the new turbine. The hybrid wind turbine can not only capture the additional energy but can decouple the generated power and wind speed with the embedded storage. The embedded storage in the hybrid wind turbine does not only function during time periods with excessive wind energy, but can also operate during time periods with lower wind speeds depending on market conditions.
- Considering the CAISO example illustrated in Fig.R1, during **Period A,** the market price is negative, the wind speed is around the rated wind speed, i.e., 12 m/s, for the 2.5MW wind turbine. Because of the negative price in Period A, traditional wind turbines usually curtails the available kinetic energy due to the lack of dispatchability. Meanwhile, the hybrid wind turbine can charge the embedded mechanical storage with available kinetic energy both for the less than rated speed periods and above than rated speed periods, and then shift the stored energy to periods with positive electricity price. For **Period B,** the market price is positive but low, and the optimal choice of traditional wind turbine is to sell the wind power to the grid while the proposed hybrid wind turbine can shift power in Period B to **Period C** which has a higher price than that in Period B. These benefits are the true value of the flexibility of the proposed design.
- Last but not least, for the case in Fig.R2, we only compared the behavior of traditional wind turbines and hybrid wind turbines in the energy market. However, the gained flexibility allows the hybrid wind turbine to provide ancillary service for the grid, which will provide extra economic benefits to the owner of the wind farms and operational benefits to the owner of power grids, as we illustrated in the Inner Mongolia case in Fig 4 in the revised manuscript.

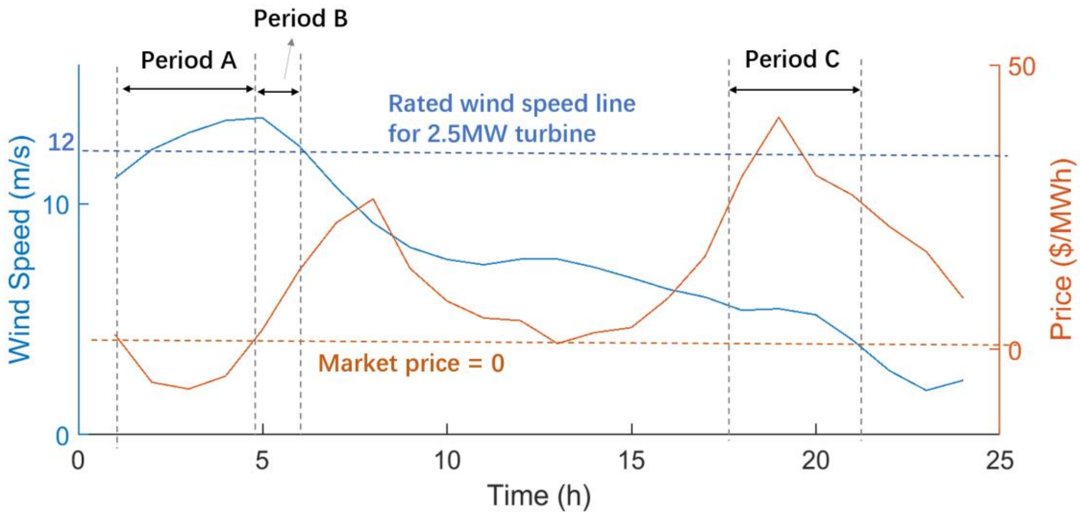


Fig. R2 Comparison of market behavior of traditional wind turbines and hybrid wind turbines during different wind conditions and market price scenarios with the CAISO market in the U.S.

6) p. 9-12 The economic projections in US and China markets are nice, however the case for the energy production claims has not been made sufficiently to justify this modeling.

The engineering and energy calculations need much more detail and rigor before proceeding to economic modeling as justification for the proposed turbine alterations.

Reply:

- Thanks for the question. Engineering and energy calculations are elaborated now in the supplementary information. As noted above, the detailed torque, weight and cost analysis for hybrid wind turbine structure and design are given in sections 2, 3 and 9. In addition, we provides a detailed analysis on internal force, pressure and efficiency, presented in section 4 in the supplementary information. A set of typical parameters are summarized in section 10.
- As presented above in Fig R1, the rotation speed is increased up to 2.69 rad/s at higher wind speeds, and the maximum torque on the shaft would increase by 66.86% at higher wind speeds. The introduction of CVT and VDM, as well as the increased weight of drive train accounts for 10.30%~15.49% of the mass of turbine top (including rotor and generator), 1.04%~1.60% of the total weight of the turbine.
- As illustrated in section S4, an engineering model of the torque and pressure of VDM determines the control solution of CVT and VDM to determine their reference power point during practical operation. We've demonstrated that the hybrid WT can keep a high-efficiency operation of CVT and VDM under a wide range of wind speeds due to the resulted control solution for CVT and VDM, with a nearly constant charging and discharging efficiency, and results a 64% round-trip efficiency over a broader wind speed variations. Subsequent internal power flow and scheduling models are based off the rigorous engineering model, employing a constant efficiency noted above. Thus, the economic analysis was based on rigorous system analysis. We omitted this part in the original submission to improve the readability of the SI, but the economic analysis and dispatch model are not affected by the added torque and weight analysis.
- To simplify the calculation for over 6000 locations, we attribute the impact of internal engineering terms to the charging and discharging efficiency of the embedded mechanical storage in the hybrid wind turbine. Such an approach has been widely used in the operational analysis of the power grid. In addition, we added detailed analysis of the charging and discharging efficiency of the hybrid wind turbine in *Section 4-4)* of the revised supplementary text.
- We noted that the major benefit is on the power market and power system integration, NOT the extra energy harvested. The results have shown clearly that **the carbon saving cost could cut by 50%, and electricity market revenue could double** when using the hybrid wind turbine for important areas in China and the U.S.

7) p. 13 The results indicate that cost-effectiveness for the revised design is fully justified for both the U.S. and China.

This conclusion is not supported by the material presented in this paper.

Reply:

- Thanks for bringing up the critical confusion on this part. There are some major misunderstandings regarding the benefit of the hybrid wind turbine. The primary benefit is on the power market and power system integration, NOT the extra energy harvested. As discussed above, imbedded storage not only function when wind speeds is higher than rated speed, but also operates at lower wind speed to reconcile the mismatch between generation and power demand. The critical dispatchability is the true value for the proposed design, leading to significant reduction of carbon saving cost and notable increase of revenue in electricity market for important areas in China and the U.S.
- Fig.3F has shown that the revenue in the electricity market has **doubled** for California, the most important state in the U.S. in terms of decarbonization.
- Fig.4C has shown that the decarbonization cost in Inner Mongolia, China is cut **by 50%** with the proposed hybrid wind turbine compared with traditional ones with the same installed capacity.
- Compared with the above benefits, the cost increase only amounts to 10%-15%, and thus we are safe to say that the cost-effectiveness is fully justified. The benefit from enhanced dispatchability is less intuitive than increase of energy production, and thus we have emphasized this part in the updated manuscript.

[Part 2] Detailed comments on SUPPLEMENTAL INFORMATION

Page # Paper text
Comments
1) S p. 2-8 COMMENT: The range of equations presented appear to represent a reasonable thermodynamic model (though more detailed information from authors would be required to ascertain that). It appears these theoretical equations with applied boundary conditions were used in the modeling. The equations were not evaluated in detail as the practical operation of the units is considered more pertinent to evaluation of the system.

There are no operational equipment specs provided, though the manufacturer specs were provided for the wind turbines which was used as the basis for the subsequent modeling. The turbine manufacturers can provide power curves based on actual performance testing with power curve estimates arrived at via power output and wind speed binning.

The lack of these specs lead to a host of questions on operational practicality (only small sample here).

Reply:

- Thanks for the questions related to the operational practicality and specifications. The previous equations on wind turbine operations are actually based off detailed modeling of internal structure, force and torque analysis. Now we have presented a full set of detailed analyses in the updated supplementary text. The detailed mechanical structures and operation mechanisms for critical sub-components of the HWT are elaborated in section S1. Changes in torque and modifications on mechanical control of the hybrid WT wind turbine are elaborated in section S2. Increase of mass for turbine top and enforcement of tower and foundations are presented in detailed in section S3. The internal force, torque, pressure and efficiency for critical mechanical add-ons are quantified in section S4.

- Through the analyses in section S2 and S3, we concluded that the rotation speed is increased up to 2.69 rad/s at higher wind speeds, and the maximum torque on the shaft would increase by 66.86%. Consequently, enforcement of tower and foundations, due to the introduction of CVT/VDM and increased weight of lower speed shaft, are also presented. These assessments lead to the cost analysis in section S9.
- Through analyses in section S4, the engineering model of the torque and pressure of VDM is provided first, and control solution of CVT and VDM to determine their reference power point during practical operation is given. These rigorous modeling leads to the quantitative analysis on efficiencies, which is the basis of dispatch and bidding model presented in sections S7 and S8.
- Full sets of parameters for design and operation of hybrid wind turbine are given in section S10. We have added relevant descriptions also in the main text. Several detailed explanations as follows.

**** What is the rotational speed of the shaft operating the CVT and VDM?***

Reply:

- The blade rotational speed and shaft torque are illustrated in Fig. R1 of the response to the previous questions. As indicated, the rotation speed is increased up to 2.69 rad/s at higher wind speeds in Region II and Region III. Wind blades for conventional turbines are designed in general to survive under 70m/s wind conditions for conventional turbines [R11]. Thus, the increase in the rotation speed does not pose a threat to the wind blade of the proposed hybrid WT, and the blade mass stays unchanged. The maximum torque on the shaft would increase by 66.86% at higher wind speeds, and correspondingly the lower speed shaft (attached to the rotor) requires a major reinforcement. We note that the higher speed shaft (used to connect to the generator) remains unchanged as the rating of the electrical generator is constant.
- The analyses related rotational speed and torque are presented now in section S2 of the supplementary information.

**** How much air is compressed per kWh?***

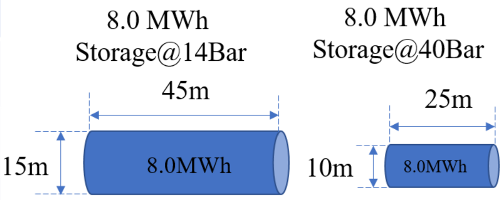
Reply:

- According to the thermodynamics associated with air compression process of the hybrid wind turbine, the mass of compressed air is mainly influenced by the adiabatic efficiency and the air compression ratio. Taking the air compression ratio as 14, which corresponds to an energy density of 1.03kWh/m^3 as indicated in Table R1, into consideration, the compressed air mass of 1kWh energy is 21.92 kg with the adiabatic efficiency as 0.8.
- Besides, we list the energy density of the mechanical add-on in the proposed hybrid WT in Table R1 with respect to the maximal air pressure in the air storage unit in Table R1. It should be noted that the maximal pressure we listed in Table R1 is 70 Bar, while for the widely-used steel-pipeline in West-East Gas Transmission of China, its maximal pressure can reach 120

Bar, and we've built a pilot compressed air energy storage system based on steel-pipeline air storage techniques in [R14]. Thus, the presented energy density is conservative and can be improved.

Table R1. The energy density of the mechanical add-on in hybrid WT.

Pressure (Bar)	14	30	40
Energy (kWh)	1.03	2.83	4.10
Pressure (Bar)	50	60	70
Energy (kWh)	5.43	6.82	8.26



*** What kind of O&M costs are associated with the CVT and VDM? How does intermittent operation with variable wind speeds and frequent necessity of reversing operation (due to wind variability) impact longevity, efficiency and performance of these parts?***

Reply:

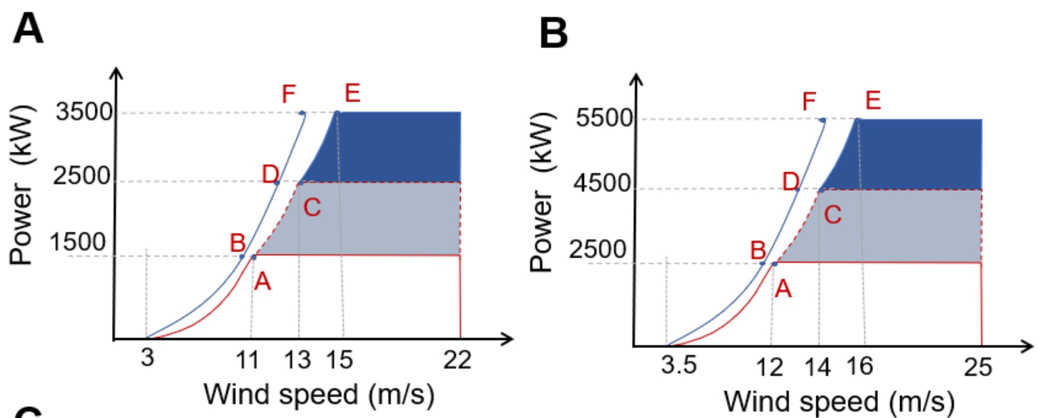
Thanks for the comments on the O&M and longevity, efficiency, and performance of CVT and VDM due to the specific operation scenario, i.e., the variable wind speeds and frequent reversing operation in the proposed hybrid wind turbine. The hybrid wind turbine leverages knowledge from the wind industry and compressed air energy storage industry, and the mechanical add-ons are commonly coming from CAES. Thus, we first answer related concerns with experience from currently commercialized CAES plants and highlight the difference in the hybrid wind turbine case if it exists.

- **The O&M cost of CVT and VDM.** CAES is not a new technology, and its history can date back to the 1940s, and two famous CAES plants, Huntorf plant in German and McIntosh plant in the U.S., have been built in 1978 and 1991 respectively. These two plants are still working well to support peak-shaving and integration of renewable energy [R15, R16]. The O&M costs of the proposed wind turbine are similar to that of these plants.
- **The longevity of CVT and VDM.** From the 40-year's longevity of *Huntorf plant* and almost 30-year's working experience, we can conclude that the longevity of CVT and VDM is enough for its application in the proposed hybrid wind turbine. Note that, both the Huntorf plant and McIntosh plant are originally built for supporting the black-start and reserve of the power grid in last century, from the beginning of this century, their roles changing to boost the integration of renewable energy. Given their 40-year operational experience, the deprecation on the longevity of CVT and VDM could be ignored.
- **The efficiency and performance of CVT and VDM.** Accompanied with the original control variable in the VDM of automobile industry, i.e., the wobble plate angle, the control pair of wobble angle and piston displacement of the VDM in the hybrid WT can guarantee the relatively constant charging efficiency and discharging efficiency of 80% under a broad range of compression and expansion power, i.e., under a wide range of wind speeds and load demands. We have elaborated the efficiency analyses in a following question. More details on the efficiency concerns can refer to section S4 of the revised supplementary text.

**** How much energy (kWh) is consumed in the compression by the VDM? How much does it vary if the wind speeds are 12 m/s vs 20 m/s?***

Reply:

- Thanks for the question. The energy consumed in the compression by the VDM varies with the real-operation of the VDM because it can be charged with rated design power and non-rated design power. As indicated in Fig. R3(A), the rated charging power for the VDM of 1.5MW turbine is 3.5MW (Point E), which can guarantee to produce ~1.5MW rated power (considering the round-trip efficiency of VDM) even if there is no wind under the condition of enough energy has been stored. Besides, we also provide another kind of design with different VDM power capacities (Point C). As indicated in Fig. R3(B), for the 2.5MW wind turbine used in the U.S. cases, the rated VDM power is 5.5 MW, which can guarantee to provide ~2.5MW rated power for the periods when there is no wind. Similar to 1.5MW wind turbine, we also provide other designs to consider different VDM power capacity.
- Last but not least, we can also shift the power curve for the proposed hybrid wind turbine to extend its application in other wind conditions, as in Fig. R3(C), and the term 'E' in "WT-E", "VDM1-E", and "VDM2-E" represents the extension of the wind blade.



C

Point	WT Type	Point	WT Type	Point	WT Type
A	WT	C	VDM1	E	VDM2
B	WT-E	D	VDM1-E	F	VDM2-E

Fig. R3 Parameter settings and operation points explanation for the hybrid WT with 1.5MW and 2.5 MW rated power capacity.

**** What size storage tank is needed if the turbine operates with wind speeds at 20m/s for 4 hrs or 12 hrs?***

Reply:

Thanks for the question on the energy density. As indicated in Table R1, the size of the storage tank is related to the maximum air pressure of the air tank. For the widely-used steel-pipeline in West-East Gas Transmission of China, its maximal pressure can reach 120 Bar, and we've built a pilot compressed air energy storage system [R14] based on steel-pipeline air storage techniques as indicated in Fig.R4. In practical engineering, we usually choose higher storage air pressure to save the volume of air tank. Assuming that we choose a 60 Bar air storage tank, which is generally lower than the maximum air pressure of the aforementioned Huntorf and McIntosh plants. For the 1.5MW hybrid WT (the type VDM2 in Fig.R3), the available kinetic power is 3.5 MW if all these kinetic energies are stored (no power output to the power grid) at 20m/s wind speed. Then, the volume of the storage tank can be ~2,000 m^3 and ~7,600 m^3 for 4 hours and 12 hours, respectively, and these two storage volumes can be realized with a matrix-form arrangement of 4 steel pipeline based air storage tanks, with each has the length of 10 m and radius of 4 m and 7.8 m, respectively.

**** How is the system sized - for maximum wind years? Then you have over capacity all the other years***

Reply:

Thanks for the comments regarding the sizing issue of the hybrid WT.

- First, we use the most popular wind turbines to conduct all the analysis associated with the hybrid WT. We choose the 1.5MW wind turbines to investigate the benefits of hybrid WT in China, and 2.5MW wind turbines to investigate the benefits of hybrid WT in U.S. For the 1.5 MW conventional WT, the parameter is adopted from GoldWind and indicated in Table S4(A) of the supplementary text. For the 2.5 MW conventional WT, the parameter is adopted from General Electric and indicated in Table S4(B). We note that all the comparative investigations are based on identical generator (electrical power) capacity for conventional WTs and the hybrid WTs.
- Second, for the energy storage capacity for the hybrid WT, we set a universal 12h storage for maximal electrical power capacity to simplify our investigations over 6000 sample locations in both China and the U.S. This provides a higher estimate of costs for locations with less windy conditions, as storage size and capacity for VDM could be reduced.
- Third, we noted that the size of energy storage capacity can be decoupled with the electric power capacity by providing several standard power capacity for VDM based on the available electrical power capacity of generator, as indicated in section S5 (Notes on VDM sizing and energy density) in the supplementary text. As a result, the size of air tank and thermal storage can be region-specific, we can easily determine the energy capacity based on the wind conditions and the power systems the hybrid WT integrated in. To determine the optimal size of the mechanical storage, multiple years of wind data could be employed.
- We have incorporated the above analysis in the supplementary text.

**** At what temperature does the thermal rock storage operate at?***

Reply:

The temperature of thermal rock storage depends on the air compression ratio of the VDM, and it can be calculated according to the temperature dynamic of the air compressor in [R14]. For the standard design with an energy density of 1.03 kWh/m3, the thermal rock storage operate at ~693 K. With the increase of the designed energy density, the temperature can be increased, and for the energy density of 6.82 kWh/m^3, the temperature can reach ~1000K. Such temperature is acceptable for thermal rock storage, as investigated in [R17] and [R18].

**** Is the thermal storage negated on cold winter days or hot summer days?***

Reply:

- Yes, the ambient temperature will impact the thermal energy storage. However, based on the practical results on the widely used concentrating solar power plants in [R17] and the thermal storage experiments associated with a practical pilot compressed air energy storage plant in [R18], such impact can be neglected due to the facts that (a) the period of the charging and discharging cycle of thermal energy storage in the hybrid WT usually less than one day and (b) the insulation measures are mature for thermal storage and could function well.

**** How much energy is it capable of being produced via thermal expansion augmentation?***

Reply:

- The energy that can be produced through air expansion relies on the wind turbine design, as indicated in Fig.R3. For the standard design (Point E), we assumed that the rated power produced by the air expansion of VDM can realize a rated electric power if enough energy is stored even when there is no wind available.

**** How is system performance impacted by variable wind speeds?***

Reply:

- Thanks for the questions. For the hybrid WT, the variation of wind speeds leads to the variation of the charging (input) and discharging (output) power of VDM. Owing to the coordinated control of the rotation speed of CVT and the control of wobble plate angle and neutral piston displacement of VDM, illustrated in section S2 (modifications/changes on mechanical control) and section S4 (control solution of VDM) of the supplementary text , the impact of variable charging VDM power and discharging power on the whole system performance is small, and the impact of variable wind speeds as well. We shall elaborate in the answer of round-trip efficiency of next question that the proposed mechanical modification on VDM and control solution can guarantee a relatively constant charging efficiency of 80% and discharging efficiency of 80% under a wide range of wind speeds and load demands. More details can refer to section S4 (efficiency on variations of wind conditions) and next question as well.

**** There are energy losses in every conversion beginning with tapping energy off of the high-speed shaft of the wind turbine power train to the CVT to the VDM to the storage tank and back to provide supplemental energy when wind speeds are low. What is that round trip efficiency? This is a critical factor that affects all of the subsequent economic projections.***

Reply:

- Thanks for the question regarding round-trip efficiency. The energy loss in the energy conversion processes associated with the mechanical add-ons is indeed a major factor that influence the round-trip efficiency. To analyze the round trip efficiency, we first analyze the charging efficiency and discharging efficiency of VDM under different wind speed. Considering the fact that the variation of wind speed impacts the charging power and discharging power of the VDM, we investigate the variation of VDM charging efficiency and discharging efficiency under different charging power and discharging power.

- For conventional rotationary machines, like the compressor (charging mode of the VDM) and expander (discharging model of the VDM), their efficiencies can vary with the charging and discharging power. The efficiency reaches the highest at the rated power point, and it decreases a lot along with the variation of charging and discharging power of compressor and expander. This is the so-called part-load efficiency issues that occurred in the compressor and expander of the gas turbine and compressed air energy storage plant, as indicated in Figure R5 and Figure R6.
- The fundamental reason for the part-load efficiency is the mismatch between the rated power capacity and variable real-time compression and expansion power, and it's is valid for the hybrid wind turbine if one only borrows the VDM from other industries without any reasonable modification. To overcome such issue, we introduced CVT to adjust the rotation speed for VDM. In addition, another control freedom for VDM, i.e. the neutral piston displacement is introduced (to adjust the working condition, see detail in section S4). These two measures allow the VDM to achieve higher efficiency in a wide range of charging/discharging power. As indicated in Fig. R5 and R6, the coordinated control of the rotation speed of CVT (adjust the rotation speed of VDM) and the control of wobble plate angle and neutral piston displacement of VDM, can guarantee the relatively constant charging efficiency of 80% and discharging efficiency of 80% under a broad range of compression and expansion power, i.e., under a wide range of wind speeds and load demands.

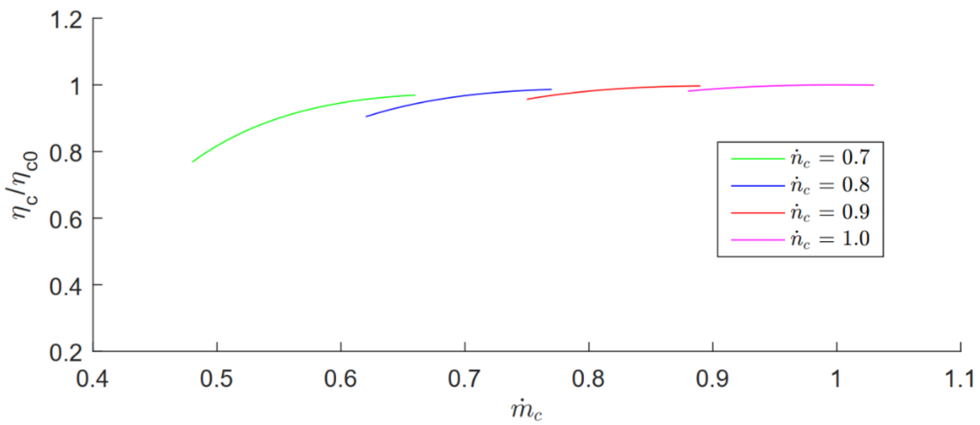


Figure R5. An example of the part-load efficiency behavior of air compressor. n_c is the rotation speed of air compressor, m_c represents the mass flow rates of air (corresponding to charging power), and subscript 0 represents the rated value at rated operation point.

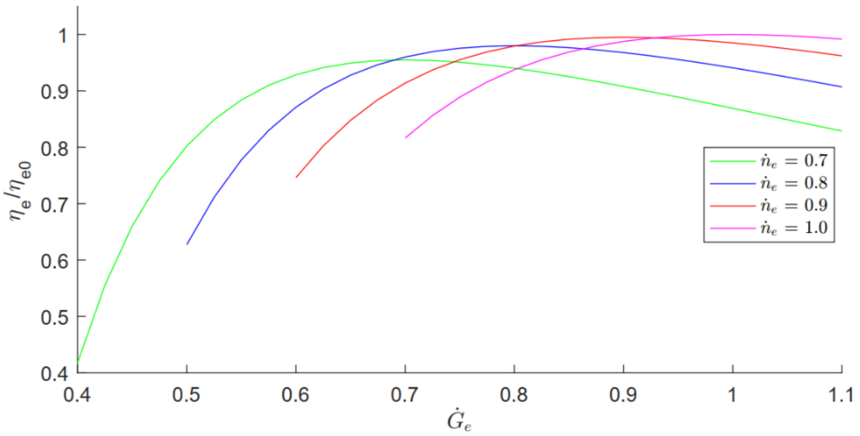


Figure R6. An example of the part-load efficiency behavior of air expander. n_e is the rotation speed of air expander, m_e represents the mass flow rates of air (corresponding to discharging power), and subscript 0 represents the rated value at rated operation point.

- Since the charging (air compression) and discharging (air expansion) efficiency can keep a nearly constant value as 80% under a variety of wind speed, we set the charging efficiency of VDM and discharging efficiency of VDM as 80% as indicated in Table S4 (Parameter settings for the 1.5MW and 2.5 MW hybrid WT and WT) of the supplementary text. Thus the round-trip efficiency of the mechanical add-ons embedded on the hybrid WT is about 64%, which is consistent with the round-trip efficiency in CAES investigation of NREL [R19], the famous A-CAES project in Europe [R20], and the AA-CAES plant in China we reconstructing [R21].
- Round-trip efficiency is a critical factor for the economic projections of the hybrid WT for wind farms and power systems. Nevertheless, as indicated in above analysis, with the coordinated control of the wobble plate angle and neutral piston displacement, the VDM can operate nearly a constant charging efficiency and discharging efficiency over a broader range of wind speed. Moreover, the efficiency parameters we adopted are also in line with the round-trip efficiency in practical CAES plants. Thus, we believe that our results on economic projections are reasonable.

**** There are no weight or size dimensions give for the CVT and VDM that would be added into the nacelle. There is no space for these systems in the nacelle. The entire nacelle and tower would have to be re-designed to accommodate the added machines and their weight.***

Reply:

- The structural redesign due to the increase in torque and weight has been taken into consideration since the first pattern in 2015 [R10]. The previous manuscript, considering the readability for a general readership, only provided final results for incremental costs (reflecting the changes in torque, weight, etc).
- We've provided a detailed analysis of the necessitated redesign to recycle the wasted wind kinetic energy through analyzing the toque balance of the shaft, the mass variations of such a

redesign, and its impacts in Section S3 of the revised supplementary text.

- We noted that the heaviest part, the storage tank is placed on the ground, which reduced the weight increment significantly. Our analysis indicates that the introduction of CVT and VDM, as well as the increased weight of lower speed shaft in the hybrid WT accounts for 10.30%~15.49% of the mass of turbine top (including rotor and generator), and the increased top mass only accounts for 1.04%~1.60% of the weight of the turbine. The detailed numbers are given in Table R2.
- Such mass increase leads to an about in 10.59%~15.86% increase of tower mass, and strengthen of the foundation by 10.56%~15.82%. Noted that turbine tower and foundation are relatively less expansive, these parts only attributes 2.04%~3.01% of increase of the total costs, and was not a primary challenge for the implementation of hybrid wind turbine.

Table R2. Component Mass of the 2.5 MW hybrid WT and 2.5 MW WT.

Component	WT	Hybrid WT (Optimistic)		Hybrid WT (Pessmistic)	
	Mass(kg)	Increment	Mass (kg)	Increment	Mass (kg)
Rotor	**66578.42**		**66578.42**		**66578.42**
Blades	39169.19		39169.19		39169.19
Hub	18136.10		18136.10		18136.10
Pitch mchnsm & bearings	7943.62		7943.62		7943.62
Spinner, Nose Cone	1329.50		1329.50		1329.50
Drive train,nacelle	**59856.55**		**72877.96**		**79435.06**
Low speed shaft	8477.90	69.91%	14404.80	69.91%	14404.80
Bearings	1196.31		1196.31		1196.31
Gearbox/ **(Gearbox+CVT)**	14061.76	16.94%	16443.82	21.38%	17068.16
Mech brake, HS cpling etc	497.34		497.34		497.34
Generator/**(Generator+VDM)**	14306.15	32.94%	19018.60	74.41%	24951.36
Variable spd eletronics	0.00				0.00
Yaw drive & bearing	6114.52		6114.52		6114.52
Main frame	11733.36		11733.36		11733.36
Electrical connections	0.00		0.00		0.00
Hydraulic, Cooling system	200.00		200.00		200.00
Nacelle cover	3269.22		3269.22		3269.22
Control, Safety System, Monitoring	**0.00**		**0.00**		**0.00**
Top Mass	**126434.97**	10.30%	**139456.38**	15.49%	**146013.48**
Increased of top mass compared to the total weight (%)		**1.04%**		**1.60%**	
Strengthen of tower (%)		**10.59%**		**15.86%**	
Strengthen of foundation (%)		**10.56%**		**15.82%**	
Note: The tower mass for conventional WT is 1129526 kg, and the total mass is 1255960.97kg.					

2) S p.9-10 The cost for a vehicle variable speed compressor for air conditioning is \$180-\$220 (See Ref S7). Thus, the per kW cost of VDM is estimated here at \$60-\$73, and a 3.33MW VDM machine would cost \$198,000-\$240,000, as indicated in Table S2.

There is no correlation in terms of cost or performance between an air conditioner compressor that has been designed (presumably optimized) for use in an automobile and scale it by a factor of 1,000 and assume there is no added re-design or weight cost, operational limits, etc.

Reply:

- The scale of the production determines the real cost of the VDM, similar to other renewable technologies. Here we only provide an estimation at this early stage. A typical VDM in the automobile A/C system of modern, which uses around 4 horsepower (3 kW) of the engine's power, costs \$180-\$220. Thus, the cost of VDM is estimated here at \$60/kW-\$73/kW, which leads to \$198,000-\$240,000 for a 3.33MW VDM, then the increased cost of the addition of VDM is 92.09%~111.63%. We note that given the increased benefits for the Inner Mongolia system and US power markets are significant, way beyond the possible cost uncertainty of VDM.

- Besides, the proposed hybrid wind turbine is much cheaper than the conventional combination of wind farms and compressed air storage techniques, as indicated in **Fig. R7.** In the configuration in Fig.R6, there are three motors or generators, including the electric generator inside WT (denoted as M1), the motor used to drive the compressor (indicated as M2), and the generator driven by the expander (marked as M3). These machines experience significant capacity waste issues regarding different operation modes of the hybrid system. M1 experiences the capacity waste during the period with low wind resource availability, while M2 suffers 100% capacity waste in the discharging and idle modes of the compressed air power plant, and M3 undergoes 100% capacity waste in the charging and idle mode of the compressed power plant. However, the proposed hybrid wind turbine eliminates the M2 and M3 by using the VDM and generator inside the wind turbine, which leads to cost-saving for the proposed hybrid wind turbine, comparing to the conventional mechanical storage systems.

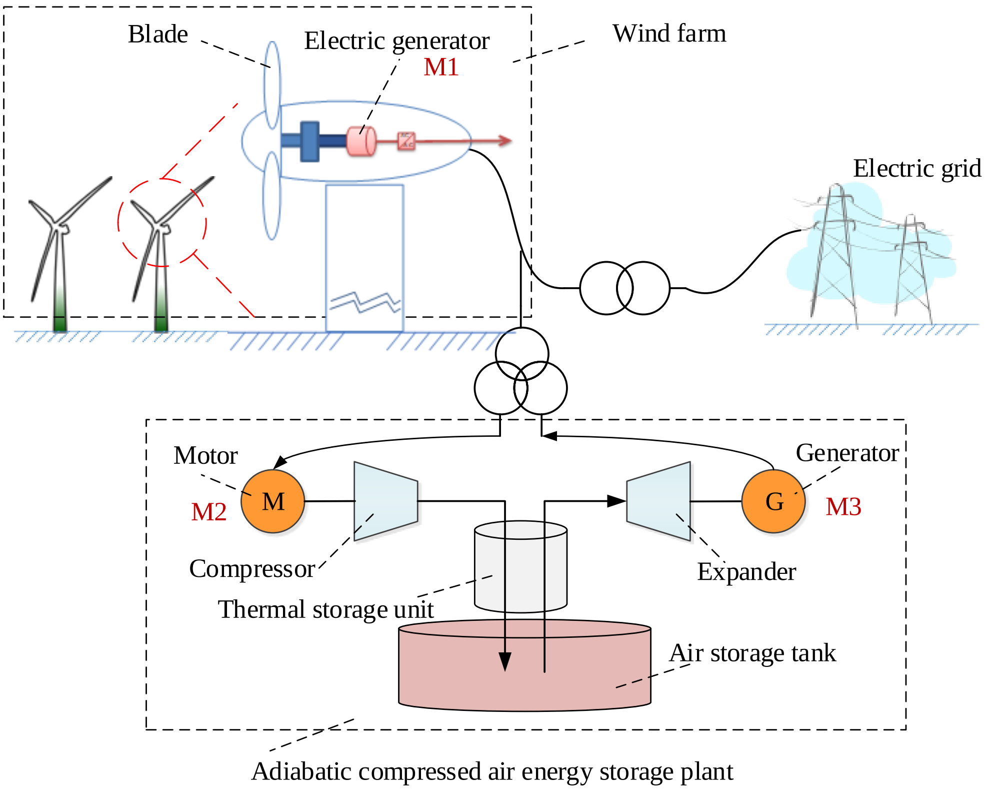


Fig R7. The conventional configuration of wind farms accompanied with a compressed air power plant.

2) Likewise, for the CVT.

The wind industry learned through costly and frequent failures during scale up of blades sizes in the mid-late 1980's and gearboxes in the 2003-10 timeframe, that simply making apparently successful blade or gearbox designs "bigger" was not prudent or practical. Catastrophic failure was rampant. Re-design of all interconnecting system parts was necessary.

Reply:

- We agree that there are challenges with increased weight and size. However, these challenges are confronted continuously with the wind industry. It was those failures paved the way of success for the contemporary wind industry, especially the blooming offshore wind sector. Taking offshore wind turbine as an example, "bigger" blades are not only feasible but also necessary. On Sep 11, 2019, siemens produced its prototype of 110m blades, which would be used in 9MW offshore wind. As a comparison, we only discussed 1.5 and 2.5 MW onshore wind turbine here.
- We do acknowledge it is necessary to go through rigorous designing testing and certification before massive deployments. But as wind turbine as a whole is expensive, the marginal costs are relatively minor for production at scale.

2) S p. 12-13 The mechanical figures in Figures S1 and S2.

The mechanical figures appear to be from the automobile application of the CVT and VDM, but they have little to do with the interface or operation with the wind turbine power train.

Reply:

- As indicated in the Fig.S1, Fig.S2, and Fig.S3 in the revised supplementary text, CVT figure brought from the automobile industry shows the concept to decouple the load from the rotation speed. The proposed VDM added a new control variable of NPD, which brings a new degree of freedom to decouple the compression/expansion ratio with the necessary/required torque. That is to say, low mechanical torque can still lead to a high compression ratio.
- The detail engineering design and calculation can be found in section 4 of the supplementary text and the operational surface as well. The operational surface demonstrated there would be a pair of control variables to run the VDM in a smooth operation space, as indicated in Fig.S5 in the revised supplementary text.

[Part 3] GENERAL COMMENTS

Outside of the windiest regions identified, the number of hours per year that the wind speeds exceed rated wind speed is a critical factor. At given site or region, the number of hours per year above rated speed would be the critical factor which be apparent in the wind speed distribution. This simple factor would eliminate a number of regions from consideration due to too few hours are above rated turbine wind speed resulting in too few hours to cover the added economics costs (based on component additions plus previously mentioned re-design, O&M, etc. costs) minus additional revenues (based on excess wind energy generation).

Reply:

- Thanks for raising this critical question. The reviewer pointed out the effective improvement concentrated in a certain geographical area (such area Inner Mongolia and northwestern China, as well as central plate in the U.S.). **These windy areas are actually the host for over 50% of the current installed capacity**, as well as over 90% of the economic wind potential in China and the U.S., as indicated in **Fig R8**. Under such a context, the proposed hybrid wind turbine function well in areas with large wind installations, which is a positive thing. For areas the proposed wind turbine does not have a real benefit, they do not have significant wind potential or existing installation either. Hence, such an argument does not influence the cost-effectiveness of the proposed hybrid wind turbine.

- Also, we want to emphasize that there is a major misunderstanding of the "cost-effectiveness." As discussed above, the major benefit is on the power market and power system integration, NOT the extra energy harvested. The results have shown clearly that the carbon saving cost could cut by about 50%, and electricity market revenue could double when using the hybrid wind turbine for important areas in China and the U.S. Fig.3F has shown that the revenue in the electricity market has **doubled** for California, the most important state in the U.S. in terms of decarbonization. Fig.4C has shown that the decarbonization cost is cut **by 50%** with the proposed hybrid wind turbine compared with traditional ones with the same installed capacity. These benefits are the ones that justified the cost-effectiveness.

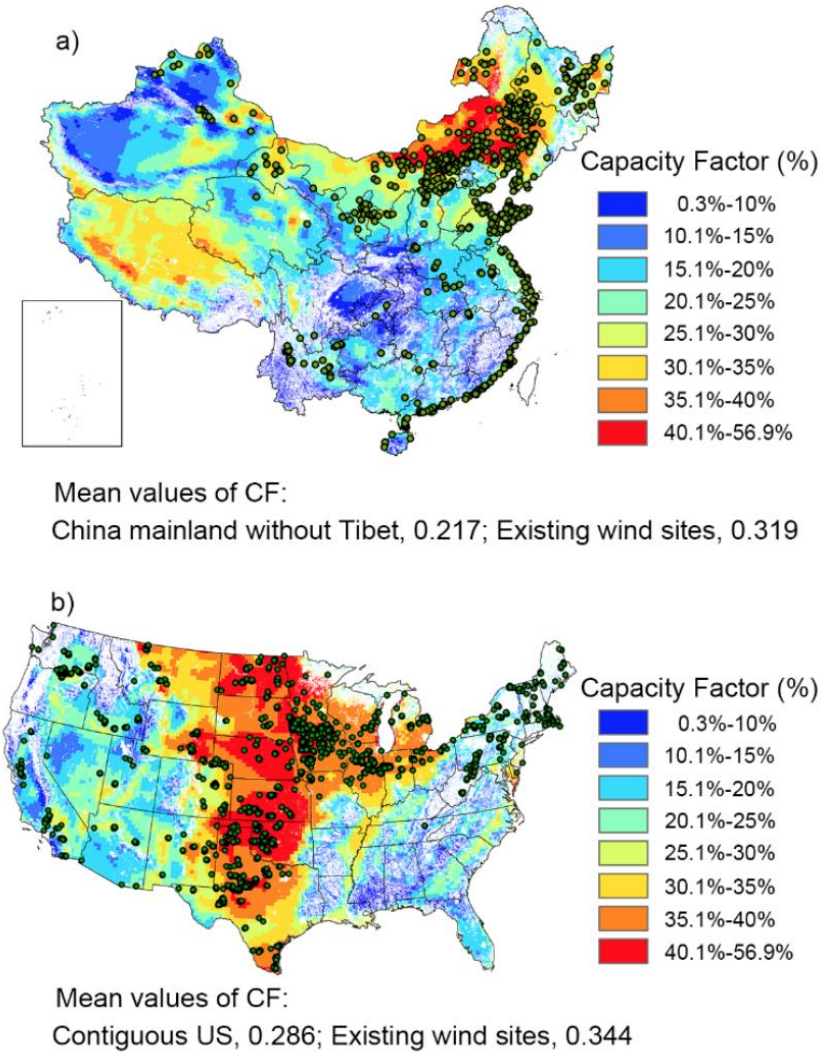


Fig R8. Geographical distribution of capacity factors and actual wind farms for US and China [R22]. The location information for wind farms in China were derived from a special report on existing wind projects in China and for the U.S. derived from a database from American Wind Energy Association (AWEA) (http://www.awea.org/Resources/Content.aspx?ItemNumber=5841&navItemNumber=5845)

No mention has been made of what the hub heights of these two turbines were or how the MERRA-2 data was interpolated to those hub heights.

Reply:

- As indicated in Table S4 in the revised supplementary text, we adopted GoldWind 1.5MW wind turbine for China, (with a hub height of 80 meters) and GE 2.5 MW (with a hub height of 80 meters) for the U.S. These two turbines are the most adopted version for China and the U.S. respectively.
- The wind speeds are extrapolated to 80 meters by the method provided in [R24], and the results have been illustrated in Fig.R9. The detailed description has been incorporated in the

updated manuscript.

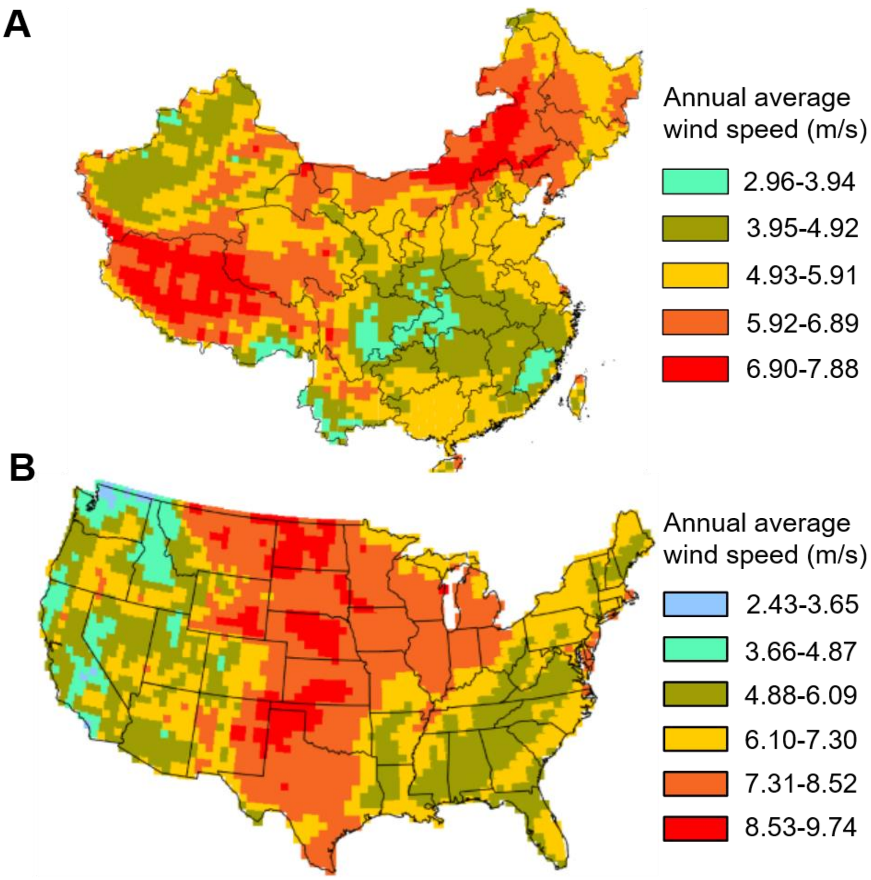


Fig. R9 Average wind speed of the samples in China and the United States.

Cross-talk referee

Overall Comments

Wind turbines are complex machines that operate in challenging environments 24/7/365. Costly mistakes have been made before with the best of intention and engineering. No one would follow the authors' proposed solution.

Please share the attachment with the authors. I pulled the info from multiple presentations (and believe I have removed everything proprietary).

To frame the challenges of wind turbine operations, some have claimed that operating a wind turbine at a reasonably windy site is like driving your car 200,000 miles per year, every year, for 20 years. I have not seen the 4 million mile car. The point: modern, utility-scale wind turbines are amazing pieces of engineering. But, we only got here after decades of decades of design, testing, failure, re-design...and optimizing continually.

Comments:

1) The best way to capture the wind energy from the higher wind speeds is with the existing wind turbine â€“ but â€œhardenedâ€� to withstand the impacts of higher turbulence and

forces at full exposure to the higher wind speeds. Manufactures did the cost-benefit analysis a long time ago and decided it was not worth trying to capture the energy from that small number of hours per year of higher wind speeds. The heavier, studier blades would not capture as much energy in the much more frequent lower wind speeds like 3-9 m/s. So it was a â€œtrade-offâ€� that was not worth the effort. And it increases the likelihood of turbine failure. Turbine failures are costly, and the resulting videos of turbine failure hurt the entire industry.

Reply:

- Thanks for sharing the turbine slides. We acknowledge the frequency distribution of the wind speed is taken into account for the wind turbine design. The procedure has been standardized to determine the trade-off between the size of the generator/rotor. However, in reality, the actually deployed turbine is dominated by the standard 1.5MW turbine in China and 2.5 MW turbines in the U.S. regardless of the local wind conditions, largely because of the economy of scale.
- We choose two typical locations in Western Inner Mongolia to illustrate the impact of wind speed distribution on the feasibility of installing the hybrid wind turbine. As indicated in **Fig. R10**, the hour percentages of wind speed higher than the rated speed are 7.28% and 27.16% for location 1 and location 2, respectively. Moreover, the kinetic energy percentages which can be recycled in the hybrid wind turbine design are 13.08% and 34.04% for location 1 and location 2, respectively.
- Based on the wind speed and wind energy distribution, location 1 may not be proper to install the hybrid wind turbine because the duration of wind speed higher than the rated speed of a 1.5MW wind turbine, i.e., 11m/s, is much shorter. Nevertheless, location 2 is feasible to install hybrid wind turbine and abundant kinetic energy available thought the duration of wind speed larger than rated speed is lower than that of low-wind speed region. In this case, conventional wisdom does not agree with the current industry practice, given the variety of wind conditions.

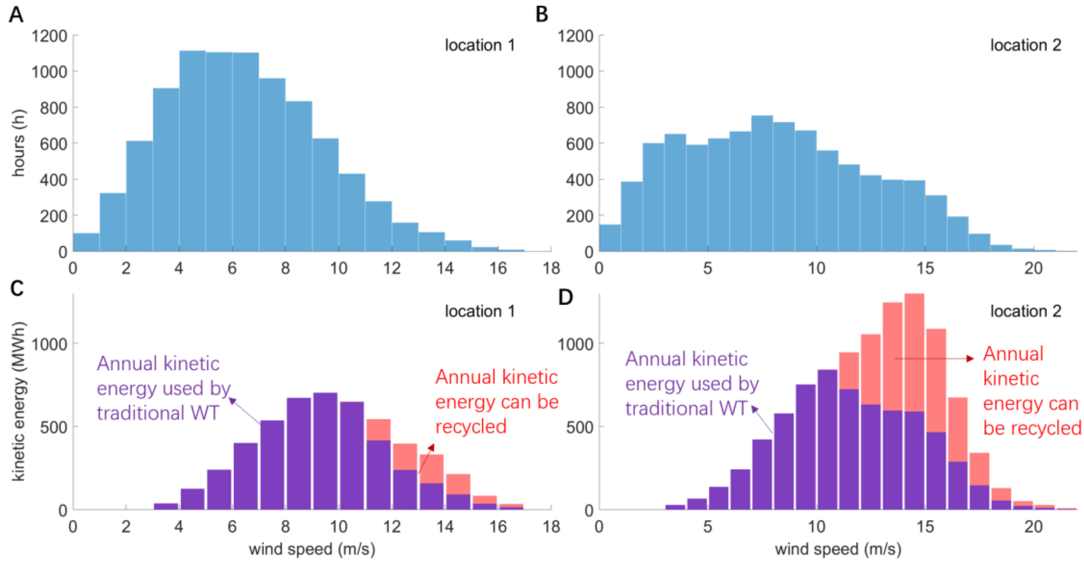


Figure R10. Annual wind speed and kinetic energy distribution of two sample locations in China. A) Annual wind speed distribution for location 1 in wind-poor areas. (B) Annual wind speed distribution for location 2 in wind-rich areas. (C) Annual kinetic energy distribution for location 1, including the kinetic energy used by the traditional wind turbine and the kinetic energy can be recycled by the proposed hybrid wind turbine. (D) Annual kinetic energy distribution for location 2.

2) No manufacturer would allow anyone to add any of the proposed devices to their turbines and honor any part of their warranty. And, they probably would not let you do it, even if you owned the turbine. Turbine failures make them look bad.

So, the paper is well-written, but to me, much more suitable for a theoretical economics journal they are looking to extract energy from a resource that appears to waste it. The equations they use to do that look right and it makes their case. Fine.

But in the world of the wind industry, where I have a lot of knowledge, I sadly do not believe this idea would pass the 'laugh test'. It is already an extremely complex machine that operates in a challenging environment, and you are talking about adding in extra machines/devices (adding friction forces, torques, etc at very disruptive location and angles) in the most difficult of the operating conditions the wind turbine faces (wind speeds above 12 m/s). Yes, engineers could enjoy the challenges of designing such devices, but no manufacturer would touch it â€“ no one has money to burn. This is a very competitive industry and mistakes are costly. The potential gains are nowhere near the potential costs.

So the paper is an exercise in "theoretical opportunity" like many good thermodynamic or economic papers. It appears to be written by outsiders looking in and believing they have found a previously undiscovered opportunity. I assure you, from inside the wind industry, that is not the case.

Industry needs practical, high reliability turbines and this approach is not that. I do not consider it to be an early stage technology. I consider it to be a not viable technology approach.

Reply:

- Since our first publication on wind power in *Science* in 2009 [R24], the levelized cost of wind power has decreased significantly, even competitive to some of the fossil fuel units in wind reach areas in the world. However, the current major barrier is the lack of flexibility in power system to accommodate the variable wind source. The cumulative loss because of wind curtailment reached 10billion RMB (over 1 billion USD) [R25-28]. What is even worse, the growth rates of wind installation is lower than 3% for wind reach areas in China, as indicated in Fig.R11. In this case, the critical challenge is not about the levelized cost or wind turbine itself, but the lack of flexibility (ability to reconcile the mismatch between power demand and wind power production) and the system integration.
- The major benefit of the proposed hybrid wind turbine is not the extra energy harvested but the valuable flexibility provided. The results have shown clearly that the carbon saving cost could cut by 50% and electricity market revenue could double when using the hybrid wind turbine for important areas in China and the U.S. Fig.3F has shown that the revenue in the electricity market has **doubled** for California, the most important state in the U.S. in terms of decarbonization. Fig.4 C has shown that the decarbonization cost is cut **by 50%** with the

proposed hybrid wind turbine compared with traditional ones with the same installed capacity. These benefits might not be apparent for people only focus on the wind turbine itself. However, these are the true benefit from a system perspective and the benefit is not travail.

- We thank the reviewer for expressing the concern from a traditional turbine manufacturer perspective. We understand that the wind industry has been successful, but we do see what is the real challenge going forward. We hope this new design could be regarded as to create an out-of-box solution that addresses the real challenge faced by the wind industry, not an industry level, incremental improvement. The quantitative analyses of turbine redesign, including torque and weight implications, has been carried out and did not alter the big picture provided.
- We have added a paragraph in the discussion section regarding the challenges towards real-world implementation. The major challenges are from too aspects:(A) We acknowledge that the rigorous testing and certification are needed before production. Government R&D funding will be required to support the initial development, as it is expected to be more costly compared with marginal improvements of conventional turbines. However, the funding scale is orders of magnitude lower than those devoted to research and piloting of grid scale battery technologies. (B) Incorporating the hybrid wind turbine into the local energy policy framework is equally important. Investments of wind power have been restricted in wind-rich, northern regions in China because of the curtailment issue, and the growth rate has dropped to less than 3% in north western and north eastern regions. China should exempt such restriction for the hybrid wind turbine given its enhanced dispatchability. In the US, the primary income of grid level storage systems is sourced from frequency regulation markets. The hybrid wind turbine, with its inherent storage capability, should be allowed to participate in ancillary service markets as well as capacity markets to further maximize the profits. Special quotas for storage have been established in parts of the US and China, and hybrid wind turbine should be eligible also for these subsidies.

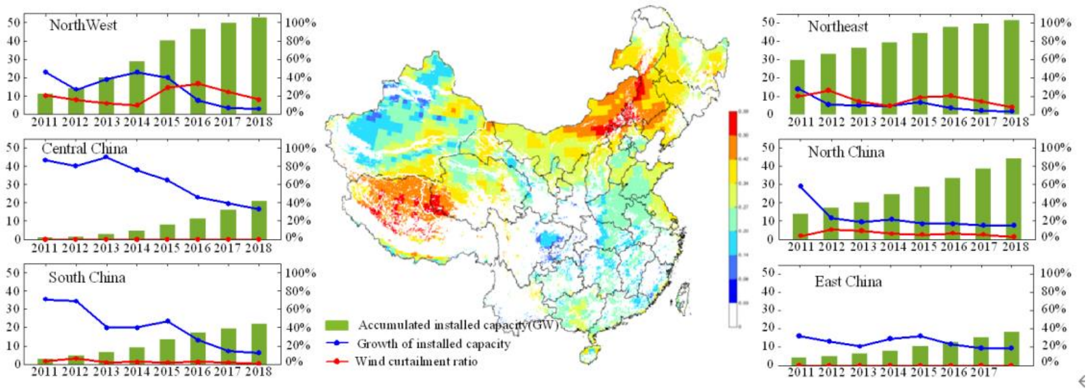


Fig. R11 Statistics of wind power capacity and wind curtailment ration in China.

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Design of Hybrid Wind Turbine with Embedded Mechanical Storage providing Dispatch Capability

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[Summary]

Wind power is one of the lowest cost, fastest growing options to reduce CO_2 emissions globally. Variability is the major barrier for its comprehensive replacement of fossil alternatives. Despite intensive efforts, battery storage remains expensive as a means to mitigate the variability. Here, we propose a novel hybrid wind turbine design with several mechanical transmission and mechanical storage add-ons. The modified system is capable of capturing kinetic energy otherwise wasted at high wind speed, releasing it at lower wind speed. It provides for higher efficiency, enabling also critical dispatch capabilities missing with conventional systems. Tested based on real-world data, we show that the reconfigured design can increase energy yields by ~20% for wind-rich areas in both the US and China, enhance revenue by 25%-100% for different US power markets, while realizing a 63% reduction in capacity required to accomodate a specific CO_2 reduction target for wind-rich regions in China.

[Keywords]

Wind turbine; Storage; Power System Dispatch; Electricity Market; Wind Curtailment

[Introduction]

As defined in the Paris Agreement, capping average global surface temperature at 2°C or preferably 1.5°C will require elimination of effectively all anthropogenic sources of CO_2 within the next few decades (*1*). Wind power is regarded as perhaps the most important renewable source of electricity. The global cumulative installed capacity of wind power increased by 3400% from 2000 to 2018 (*2*). The levelized cost of electricity from wind power declined to $0.06/kWh in 2018 (*3*), competitive with coal- and gas-fired generators, representing one of the lowest cost renewable sources. The inherent variability and uncertainty associated with wind power, however, poses a significant challenge for further replacement of fossil generators (*4*,*5*). Conventional wisdom for mitigating the variability of wind power suggests installation in power grids of energy storage systems, such as batteries (*6*), supercapacitors (*7*), compressed air systems (*8*), pumped hydro (*9*), and flywheels (*10*). These technologies may be restricted to specific geographic locations and are likely to incur significant additional costs (*11*). Here we propose a novel design for a hybrid wind turbine, with addition of several mechanical transmission and mechanical storage components. Tested based on actual wind conditions and real power system/market conditions in both the US and China, this system can reduce the fluctuations of power output from conventional turbines, improving the overall electricity yield, while enhancing system flexibility and increasing revenue in power markets with relatively minor addition of costs. The new wind turbine design offers a promising cost-effective approach for rapid de-carbonization of energy systems globally.

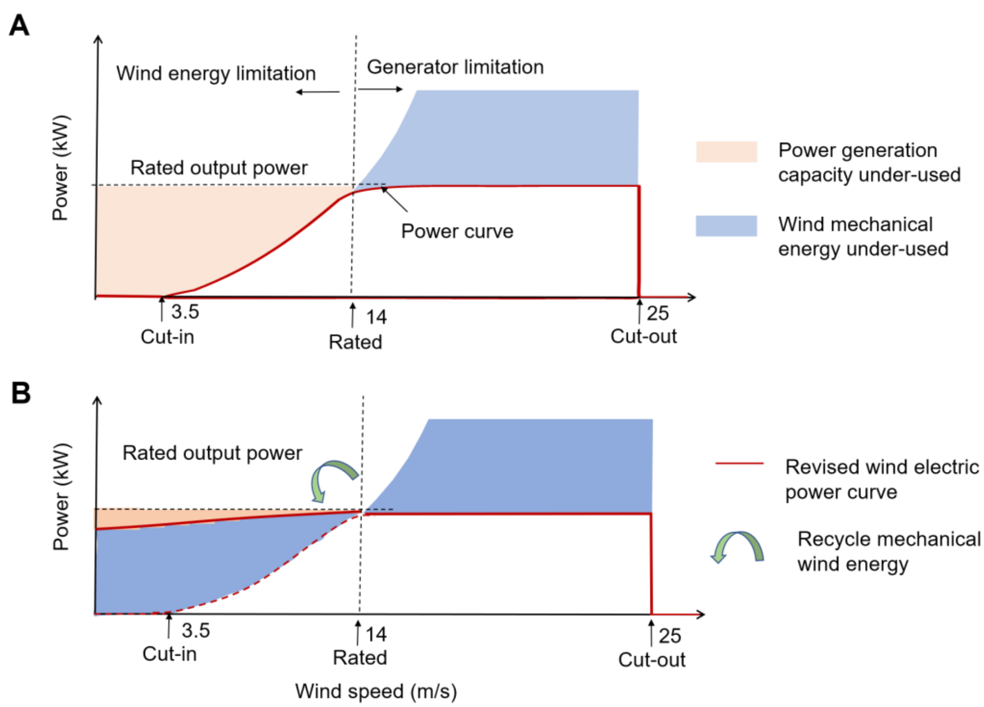
[Results]

General Principle and Design of the Hybrid Wind Turbine

A typical wind turbine includes two major components, the rotor (including blades, shafts, hub) and the generator (including gearbox, generator, DC/AC conversion components) (illustrated in Fig. 1C). The power output varies non-linearly with wind speed according to the power curve (*12*), as depicted in Fig.1A. When wind speeds are lower than the rated speed (about 14m/s) of the turbine, power output is proportional to the cube of the wind speed, and the generator operates at a status lower than its maximum capacity, with part of the generator's potential capacity idled. When the wind speed is higher than the rated speed of the turbine, the generator reaches its capacity limit (rated capacity) and pitch control is activated to reduce the fraction of energy captured by the blades, resulting in under-utilization of available wind kinetic energy. To resolve this dilemma, we propose a hybrid design capable of storing kinetic energy otherwise wasted at higher wind speeds, reusing this source at lower wind speeds taking advantage of generator capacity that would be idled otherwise. The hybrid design incorporates in the traditional wind turbine a parallel mechanical transmission and mechanical storage system. With this design, the electricity output from the wind turbine is effectively decoupled from the variation of wind speeds, providing a relatively constant output of power independent of variations in wind speeds (Fig.1B). The hybrid wind turbine provides critical operational flexibility for the system, a major barrier for integrating the variable renewables. Further, the efficiency of the hybrid wind turbine design is higher than the efficiency of traditional turbines, capturing as it does otherwise wasted kinetic energy in the range of higher wind speeds.

The detailed structure of the novel hybrid wind turbine is illustrated in Fig. 1D. Compared to a traditional wind turbine, a mechanical add-on is introduced to reform the connection between the mechanical gear transmission and the electrical generator as highlighted by the dashed box in Fig.1D. The additional components are connected mechanically to avoid the cost of the unnecessary motors and generators commonly incorporated in other storage systems (*8*, *13*). The mechanical add-ons include four key components, a continuously variable transmission (CVT), a variable displacement machine (VDM), a thermal energy storage (TES) system, and an on- or under-ground air storage tank (similar to existing compressed air storage tanks). The VDM represents a reversible compression/expansion machine (fig. S1), which can work either in a compression cycle to store wind mechanical energy (at high wind speeds) or in an expansion cycle to compensate for the wind energy deficit at low wind speeds. The CVT is deployed to adjust the rotating speed of the VDM to guarantee the high-efficiency operation of the VDM (fig. S2), such that the efficiency can reach 75~85% in a single compression or expansion operation. The TES, composed of a cheap packed bed of rocks, reduces the temperature of the high-pressure air developed in the compression cycle of the VDM before injecting this air to the storage tank, allowing for reheating of high-pressure air in the expansion cycle. Extended analyses of the mechanical add-ons, the internal forces and analyses of energy flows, as well as control algorithms are elaborated in the supplementary information.

Enhancement of drive train, strengthen of tower and foundation and increase of costs are quantified based on detailed torque, weight and pressure analyses, as presented in the supplementary information. The maximum torque on the lower speed shaft increased by 66%, leading to a 60% increase of mass for the shaft. The configuration for higher speed shaft remains unchanged, as the rating for the generator stays constant. As the heaviest part of mechanical add-on, air storage tank, is placed on the ground, the hybrid design has a relatively minor impact on mass variations. The weight increase (mainly from the VDM, CVT and lower speed shaft) in the nacelle accounted for 10-15% of the top mass, 1% of the total weight for conventional wind turbine, leading to an 10-15% weight increase for the tower and cost increase for the foundation (see details in section S3 of SI). The incremental costs associated with the hybrid design involve mainly expenses for the VDM (5%~6%), CVT (2%~4%), thermal storage (1%), air storage (1%), strengthening the tower/foundation (1%), and strengthening the mechanical transmission (less than 1%), contributing to an increase in total cost of about 11%-15% compared with the cost for traditional wind turbines of the same size and configuration (see detailed cost breakdown in supplementary information).



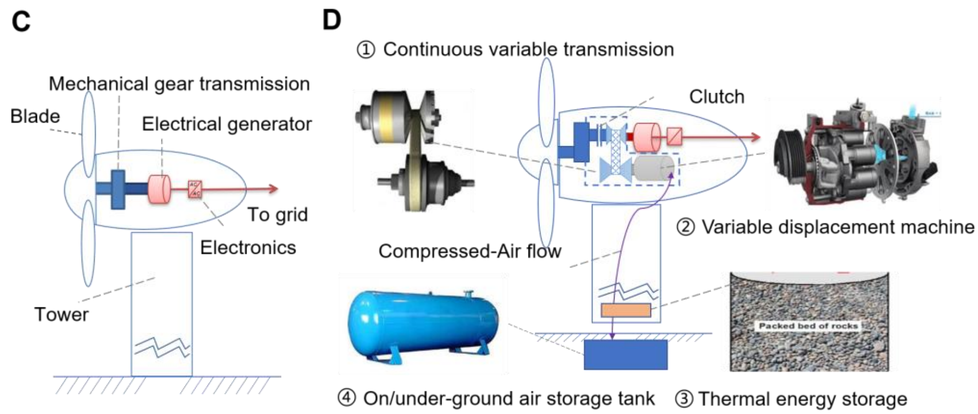


Fig.1. Fundamental operational principles and structural design for the novel hybrid wind turbine with embedded air powered mechanical storage. (A) The power curve for a traditional wind turbine, idled generator capacity at lower wind speed and under-utilized kinetic energy at higher speed. **(B)** The power curve of the proposed hybrid wind turbine, which allows for a relatively constant power output by recycling the under-utilized kinetic energy at high wind speeds to lower wind speed conditions. **(C)** The major mechanical and electrical components for a conventional wind turbine. **(D)** Illustrative diagram for a hybrid wind turbine with mechanical transmission and storage add-ons (indicated within dashed blue box).

Performance of Hybrid Wind Turbine with Different Geographical Locations

The proposed new wind turbine design, as noted earlier, can increase the total yield of electricity as a consequence of the additional kinetic energy captured at higher wind speed. To validate the effectiveness of this turbine under real wind speed conditions, we simulated the operation of the hybrid wind turbine at an hourly resolution throughout an entire year over 5000 geographical locations in both China and United States - the two largest national emitters of CO_2. Hourly wind speeds were derived from an assimilated meteorological database (MERRA-2, *14*) with geographical resolution of 0.5° by 0.65°. For illustrative proposes, we consider new designs reflecting modifications of the conventional 1.5MW Gold Wind and 2.5MW General Electric wind turbines installed commonly in the China and US respectively. The detailed mechanical structures and operational mechanisms for the new designs are summarized in the supplementary information (table S1, table S2, and Methods and Materials). The analyses indicate that the hybrid wind turbine can improve the power generation yield (indicated as the capacity factor in Fig. 2) by ~20% in wind-rich regions of both the US and China (central plain in the US and Northern China), compared with the performance of traditional turbines of the same size and conventional configuration. These regions are hosts to the majority of wind investments (5,20). Sensitivity analyses regarding blade radius, VDM power capacity, and storage capacity are presented in the supplementary information. Detailed parameters could be optimized with respect to different wind conditions to further improve performance. With an increment of 5% and 10% in blade lengths of the hybrid turbine, capacity factors could be increased by 20%~37% compared to traditional wind turbines with the same blade length increase (fig. S5).

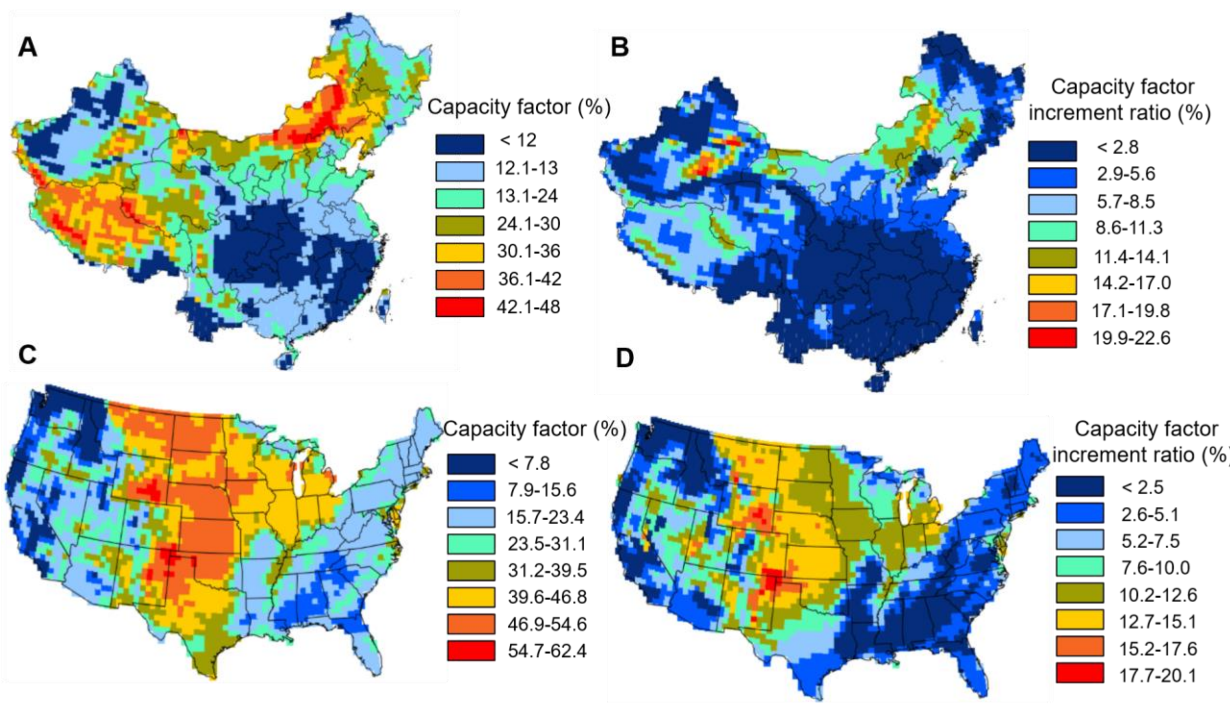


Fig.2. Electricity generation improvement with 1.5 MW hybrid WT in China and 2.5 MW hybrid in the

United States less Hawaii and Alaska. (A) Map of the capacity factors for deployment in China of 1.5 MW hybrid WTs with 2 MW VDM and 24 h storage capacity. (B) Map of the improvement of the capacity factors with the conditions envisaged in (A) with respect to deployment of conventional 1.5 MW systems. (C) Map of capacity factors associated with deployment over the continental US of 2.5 MW hybrid WTs with 2 MW VDM and 24 h storage capacity. (D) Map of the improvement of the capacity factors realized for the conditions envisaged in (C) with respect to results expected from deployment of conventional 2.5 MW turbines.

Effectiveness of Hybrid Wind Turbine for Improving Revenue in US Power Markets

The hybrid turbine can not only effectively increase energy yield, but, more importantly, it provides critical dispatch flexibility for energy systems, leading to significantly improved revenue for wind producers in US electricity markets. The revenue for wind power in power markets depends on both the electricity generation and the wholesale market price. The wholesale price varies markedly over different times of the day. At night when the wind is strong and power demand is low, the wholesale price of electricity can decline to zero or even become negative (*15*). Revenue for wind producers is limited over these time periods. The new design, on the other hand, allows for adjustment of electricity output in response to price fluctuations, since the power output and wind speed are largely decoupled. To quantify the benefits of the new wind turbine in actual US power markets, we simulated its operation with real wind speeds and actual wholesale market pricing data for all six major US electricity markets. An optimization model for scheduling the hybrid system under market conditions is summarized in Materials and Methods. The results indicate that improvements in revenue are significant for all power markets: NYISO by 32%~39.12%, MISO by 16.96%~26.19%, ISO-NE by 28.5%~35.95%, ERCOT by 26.26%~50.21%, and PJM by 24.38%~33.23% (Fig.3 A-E). The new design can increase revenue by as much as 50.40%~129.60% in the California ISO (Fig.3 F), a market with particularly volatile prices in conjunction with the higher penetration of renewables *(16)*. Note that this estimate for the increase in revenue is conservative since additional revenue streams could be derived from the capacity and ancillary service markets (*17-19*). As indicated earlier, the total costs increase amounts to 11%-15%. The increase in revenue thus outweighs significantly the incremental cost for the reconfigured wind turbine, underscoring its economic advantage.

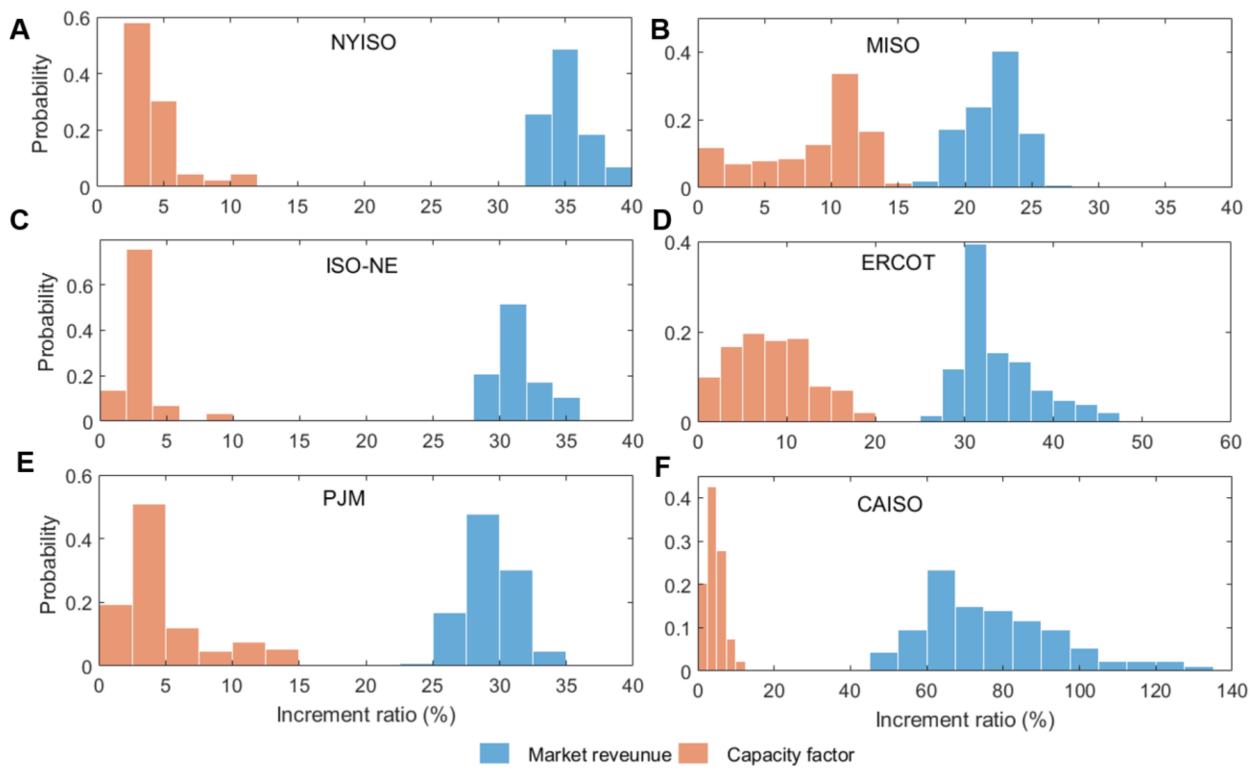


Fig. 3. Improvements of capacity factor and wholesale revenue for the proposed wind turbine compared with traditional wind turbines in all major US power markets. Capacity factor and wholesale revenues for both traditional wind turbine and proposed hybrid wind turbine are compared in 1189 sample locations within major power markets. The improvements in revenue and capacity factors for the hybrid wind turbine are illustrated for **(A)** New York Independent System Operator (NYISO), **(B)** Midcontinent Independent System Operator (MISO), **(C)** ISO New England (ISO-NE),

(D) Electric Reliability Council of Texas (ERCOT), **(E)** Pennsylvania-New Jersey-Maryland Interconnection (PJM) and **(F)** California Independent System Operator (CAISO) respectively.

Effectiveness for Hybrid Wind Turbine to Decarbonize Typical Power Systems in China

Incorporating variable wind power into inflexible power systems has been the primary challenge in achieving a higher level of penetration for renewables in China. Coal-fired generators and combined heat and power units account for 37% and 43% of the generation mix for wind-rich northern China *(20,21)*. These generation units are unable however to keep up with the variation of wind power. As a result, a significant fraction of potentially available power generation from wind is curtailed. The cumulative financial loss due to the curtailment of wind power over the past five years amounted to 10 billion USD (*22*). The hybrid system proposed here would significantly mitigate the curtailment issue, as it would result not only in less variable power output but could provide also for dispatch capability while offering a source of reserve power.

To test the effectiveness of the new turbine design, a unit commitment model was developed incorporating all characteristics of the new turbine with full considerations of power system operational requirements (see detailed modeling in Supplementary Information). Based on actual data (see Supplementary Material) for the Western Inner Mongolia power system (a provincial region with the largest wind installation in China), hourly simulations of power system operation were conducted for an entire year under different wind penetrations. The operational results for both the proposed hybrid systems and conventional turbines are illustrated in Fig. 4. Assuming 40GW of installed wind capacity, hourly power balances for a two-week time interval are illustrated in Fig. 4A. For the conventional wind turbine scenario, wind power needs to be curtailed at high wind conditions while coal-fired units have to ramp up production during less windy days.

In contrast, the proposed hybrid wind turbine would allow for a relatively constant source of power over this two-week period, substituting for almost all the of electricity generated by conventional thermal units. At this wind level, overall wind power production increased by 29% for the entire year, as shown in Fig. 4B. Assuming a carbon reduction target of 20% for the studied system, it would require installation of 62 GW of conventional wind turbines, but would need only 23 GW of hybrid wind turbines (Fig.4D). The required capacity (and the total cost) is significantly reduced as curtailment is largely mitigated at higher wind penetration with the new turbines (Fig. 4C). This indicates that the proposed hybrid wind turbine could be effective in the Chinese situation not only to improve system flexibility but also to reduce curtailment.

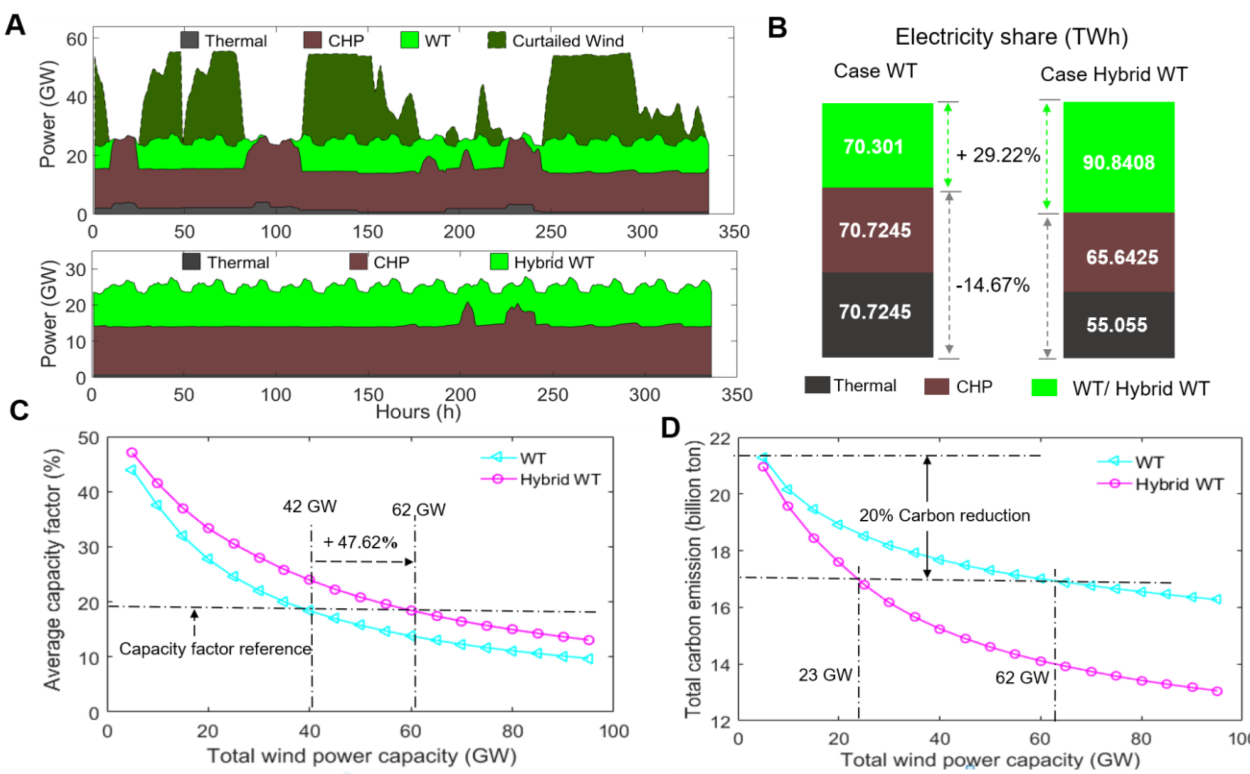


Fig. 4. Power system production simulations with hybrid wind turbines in West Inner Mongolia Grid, China. (A) Comparison of power production and energy balance over a typical two week

interval for 40 GW WT vs. 40GW hybrid WT. Hybrid WT maintains an uninterrupted electricity output and almost eliminates the need for electricity from traditional thermal power plants. **(B)** Redistribution of electricity share among different sources using 40 GW WT vs. 40GW Hybrid WT. Hybrid WT offers a 29.22% increment of wind electricity eliminating need for 14.67% of fossil fuel-based electricity. **(C)** Comparison of an improved wind power capacity penetration curve provided by the Hybrid WT. The capacity factor reference line is set at 19.14% per average wind CF in 2017. Hybrid WT can increase wind power capacity from 42 GW to 62 GW, a 47.62% increment, under the same thermal unit regulation capacity. **(D)** Comparison of total CO_2 emission reductions for different wind power capacities using Hybrid WT vs. WT; 23 GW of hybrid WT or 62 GW of conventional WT needed to realize a 20% reduction of carbon emissions.

[Discussion]

Overall, we proposed a novel design for a hybrid wind turbine. With several mechanical transmission and mechanical storage add-ons, this system is capable of capturing and storing kinetic energy otherwise wasted at high wind speeds utilizing it at lower wind speeds. We note that the primary benefit for the reconfigured design is that it enables critical dispatch capability for the new turbines in that the variation of wind speed and the corresponding power output can be decoupled. With the enhanced dispatch flexibility, revenue for the wind producer could double when adopting the hybrid wind turbine in the electricity market for California, the most important state in the US in terms of decarbonization. The cost for reduction of carbon emissions could cut in half in wind rich areas in China when employing the hybrid wind turbine, as it could largely reduce curtailments at higher wind penetration, a major barrier for wind development. The incremental cost for the hybrid turbine is lower than the cost for alternative stand-alone electrical storage systems, avoiding costs for motor/generator and AC/DC conversion components, a significant fraction of the expense for conventional storage systems. The proposed design also improves the overall efficiency by capturing additional kinetic energy. Given that the levelized cost for wind power is already lower than conventional fossil units, it is the flexibility issue that most significantly hampers the further development of wind markets under higher renewable penetrations. While addressing such central challenge, the proposed design represents a promising solution for economic, dispatchable, renewable sources of power.

Detailed structure, analysis, configuration and operational strategy have been presented for the hybrid wind turbine. For its future real-world implementation, two major aspects of the related challenges should be addressed. (A) Rigorous engineering and testing should be carried out, including real-world capability, system reliability, wear and tear remedy, durability and extreme condition performance. A series of certification procedure should be followed then. Government R&D funding will be required to support the initial development, as it is expected to be more costly compared with marginal improvements of conventional turbines. However, the amount of funding required should be orders of magnitude lower than those devoted to research and piloting of grid scale battery technologies. (B) Incorporating the hybrid wind turbine into the local energy policy framework is equally important. Investments of wind power have been restricted in wind-rich, northern regions in China because of the curtailment issue, and the growth rate has dropped to less than 3% in north western and north eastern regions. China should exempt such restriction for the hybrid wind turbine given its enhanced dispatchability. In the US, the primary income of grid level storage systems is sourced from frequency regulation markets. The hybrid wind turbine, with its inherent storage capability, should be allowed to participate in ancillary service markets as well as capacity markets to further maximize the profits. Special quotas for storage have been established in parts of the US and China, and hybrid wind turbine should be eligible also for these subsidies. We note that the hybrid design establishes a novel framework for integrating mechanical storage into the design of the wind turbine. The proposed mechanical transmission and storage systems represent one of many possible solutions under this framework, with significant room for improvements that could be realized in the future.

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Supplementary Materials:

Materials and Methods
Figures S1-S12
Tables S1-S3

Supplemental Information

Design of Hybrid Wind Turbine with Embedded Mechanical Storage Providing Dispatch Capability

Content

Materials and Methods

Detailed mechanical structures and operation mechanism, torque and structural design, mass variations and enforcement, engineering model, scheduling, and cost analysis of the proposed hybrid wind turbine (HWT) are presented in this supplementary information. The detailed mechanical structures and operation mechanisms for critical sub-components of the HWT are elaborated first. Then, the torque and structural redesigns of the hybrid wind turbine are elaborated in section 2. Mass variations of the tower top and associated enforcement are analyzed in section 3. The engineering model of torque, pressure, and parameters for HWT are formulated in section 4. Section 5 provides the investigation on the sizing and energy density issues of the HWT. Section 6 analyzes the annual wind speed and wind energy distribution to justify the operational feasibility of the HWT. Section 7 formulates the scheduling model of the HWT, and a unit commitment model to optimally dispatch the system with consideration of features for the HWT is presented in section 8. Section 9 summarizes the breakdown of the incremental costs for the proposed HWT design. Section 10 provides the parameter settings for the turbine design and operational simulations.

S1. Detailed Mechanical Structures and Operation Mechanisms of VDM and CVT

As illustrated in Fig.1 in the manuscript, the mechanical add-ons of HWT include continuously variable transmission (CVT), variable displacement machine (VDM), thermal energy storage (TES) system, and air storage tank (AST). The air storage tank and thermal energy storage are similar to those in compressed air energy storage (CAES) systems which have over 10 projects in operation or under construction in China, U.S, Canada, and other countries [S1, S2, S3]. The critical structure converting kinetic energy from/to compressed air involves VDM and CVT. Detailed structures and operational mechanisms are illustrated as follows.

The VDM is an axial multi-piston device employed to produce or consume compressed air by working as either a compressor or an expander. It consists of a driveshaft, a wobble plate, multiple pistons, and cylinders (Fig.S1). The wobble plate angle (denoted as δ) is used to regulate the compression $(\delta > 0)$ and expansion modes $(\delta < 0)$ of the VDM. The piston and air movements of one single cylinder in the compression and expansion mode are illustrated in Fig.S1B and Fig.S1C, respectively. Each piston experiences a change of position sequentially from left to right in Fig.S1B while rotating along the VDM shaft. The compression process can be divided into three phases: the closed compression, the open injection, and the open suction. In the closed compression phase, the ambient air is compressed in the closed cylinder chamber, and its air pressure has to reach the pressure of the air storage unit (ASU) at the end of this phase. The compressed air is ejected then into the ASU interacting in the process with the TES system. After ejection, the valve sucks ambient air into the cylinder in the last phase of the operating cycle.

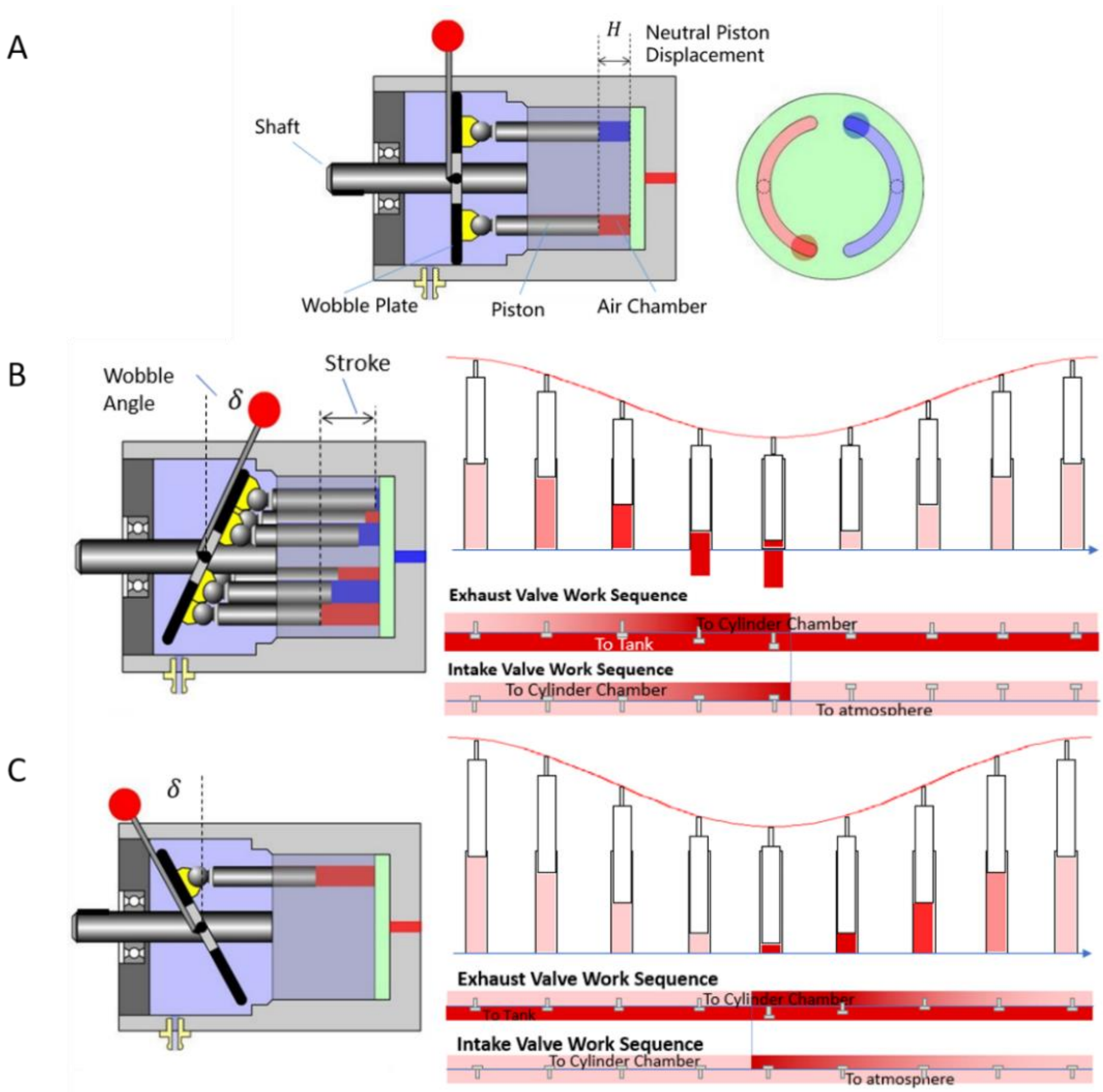


Figure S1. Mechanical structure and operation modes of the VDM. (A) The mechanical structure of the VDM. VDM is a reversible machine composed of a shaft, a wobble plate, multiple pistons, and an air chamber. (B) Compression mode of the VDM. VDM works as a compressor to store the wind kinetic energy by producing compressed air at higher wind speeds. (C) Expansion mode of the VDM. VDM works as an expander to provide wind kinetic energy by consuming compressed air at lower wind speeds.

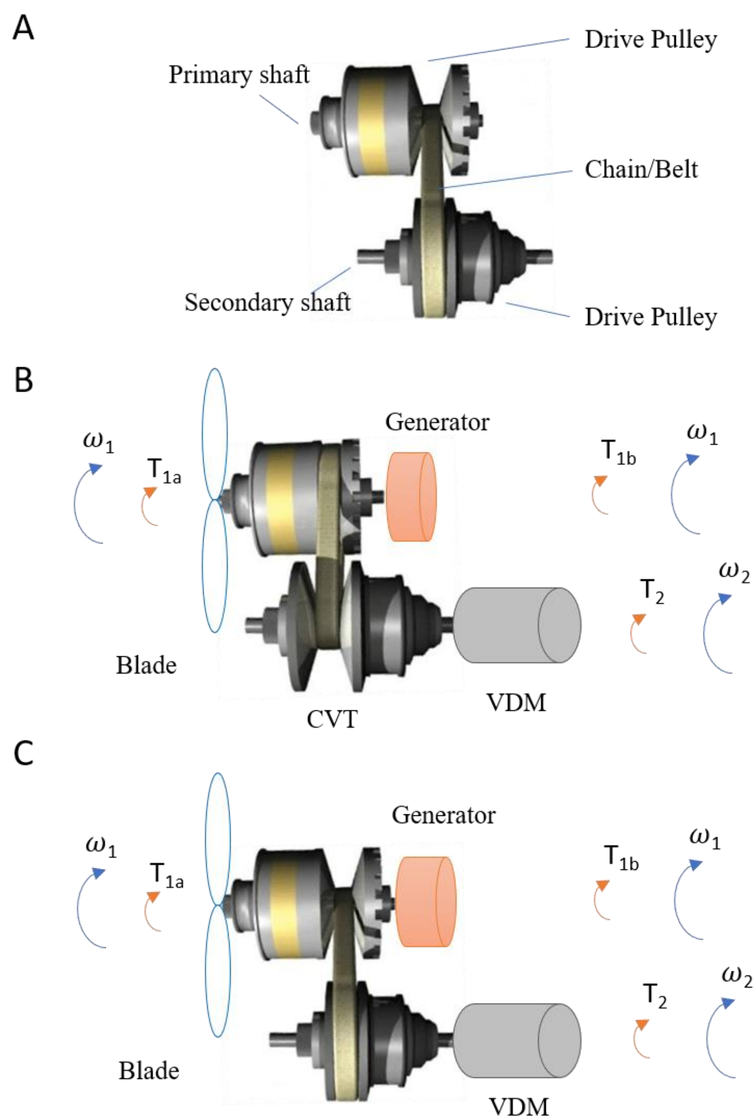


Figure S2. Mechanical Structure and operation status of CVT. (A) The mechanical structure of CVT. (B) Increasing gear state of CVT. (C) Reduction gear state of CVT.

The control parameters (δ, H), as indicated in Fig.S1A, are determined by the boundary conditions of VDM, such as the torque posed by the shaft and the pressure in the air tank, as indicated by the side view and front view of wobble plate of VDM in Figure S3, and more details can be found in section S4. With the coordination of CVT rotation speed control and the control pair (δ, H) of VDM, the compression-expansion operation can realize a 75%-85% efficiency over the entire range of the operational status of VDM.

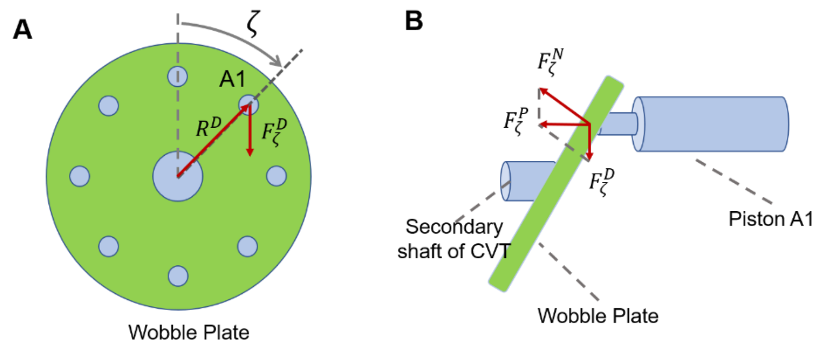


Figure S3. The wobble disk force analysis of VDM. (A) The side view of wobble. (B) The front view of wobble disk in VDM.

S2. Modifications/Changes on Mechanical Control

While introducing the mechanical add-ons for the HWT, additional torque would be imposed on the mechanical structure. In this section, we analyze the modifications on the mechanical control of wind blade, as well as changes on blade rotation speed and shaft torque.

In the proposed HWT, the operational region is divided into three segments for different operational schemes. Four wind speed points are marked on the wind power curve. The cut-in and cut-out wind speeds refer to the point the wind turbine start and stop to operate, respectively. The electrical rated wind speed is defined as the point while the wind turbine reaches its nominal electrical capacity. We bring a concept of structurally rated wind speed, which is the point wind turbine reaches the combined capacity of both the electrical load of a generator and the mechanical load of VDM. The high-speed shaft needs to be reinforced to help achieve this capacity. The difference between a 2.5 MW HWT and a conventional turbine is presented in Fig. S4.

In Region I, the segment between the cut-in speed and electrical-rated speed, i.e., 3m/s-12m/s, the wind turbine is operated on the maximum power point tracking (MPPT) strategy. Region II covers the segment between the electrical-rated speed and structural-rated speed, i.e., 12m/s-15.5m/s. In this region, the blade of HWT is still operated on the maximum power point tracking strategy. However, the electrical generator has already reached its rated capacity, and the surplus energy is diverted to the VDM up to VDM's mechanical capacity. Region III is comprised of the segment between structural rated speed and cut-out speed, i.e., 15.5m/s-22m/s, where the pitch control is activated to limit the maximum wind energy intake from the blades.

It is noted that the control strategies in Region II and III are identical for a conventional wind turbine. The blade is operated to maintain its electrical-rated capacity because the blade drive train is directly coupled to the electrical generator. In contrast, the hybrid turbine has different operation strategies in Region II and III, respectively.

As indicated, the rotation speed is increased up to 2.69 rad/s at higher wind speeds in Region II and Region III. Wind blades for conventional turbines are designed in general to survive under 70m/s wind conditions [S4] for conventional turbines. Thus, the increase in the rotation speed does not pose a threat to the wind blade of the proposed HWT, and the blade mass stays unchanged. The maximum torque on the shaft would increase by 66.86% at higher wind speeds, and correspondingly the lower speed shaft (attached to the rotor) requires a major reinforcement. The detailed configuration on weight and diameters for the lower speed shaft are given in the following section. We note that the higher speed shaft (used to connect to the generator) remains unchanged as the rating of the electrical generator is constant.

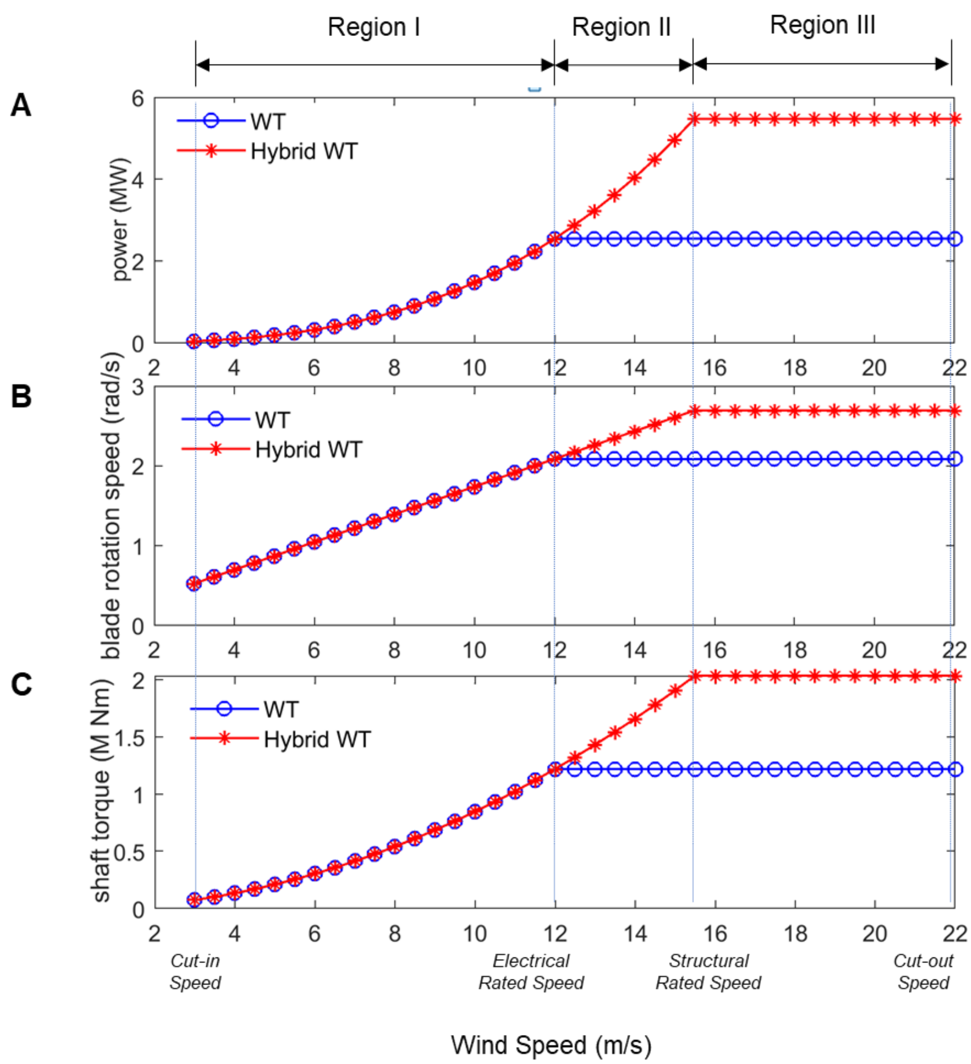


Figure S4. Comparison of blade rotation of conventional WT and the proposed HWT **with 2.5MW rated power.** (A) Power curves of WT and **HWT**. (B) Rotation speed curves of WT and **HWT**. (C) Shaft torque curves of WT and **HWT**.

S3. Impact of Weight Distribution and Enforcement of Tower and Foundations

The incorporation of the mechanical add-ons for the HWT requires reinforcement of tower and foundation due to the increased mass in the nacelle. In this section, we provide a detailed quantitative mass analysis of the HWT, as compared to the conventional turbine. The mass analysis for conventional wind turbines breaks down into rotor mass, drive train and nacelle mass, and tower mass, based on some previous studies[S6, S7]. The detailed nacelle mass increase for the HWT is also quantified. The enforcement of tower and foundations is presented. As will be indicated, the new design of wind turbine could be 1388599.18kg~1454682.30kg, mainly because of the introduction of CVT and VDM, as well as the increased weight of lower speed shaft. Such weight increase accounted for 10.30%~15.49% of the mass of turbine top (including rotor and generator), 1.04%~1.60% of the total turbine. The increase of weight in nacelle will require strengthen of the tower by 10.59%~15.86%, and strengthen of the foundation by 10.56%~15.82%, contributing to an 2.04%~3.01% increase in total cost.

1) Rotor mass

Rotor mass is composed of the mass of blades, hub, pitch mechanism and bearing, spinner (nose cone). Define R as the rotor radius, the mass of each component can be determined by:

$$\begin{cases} \text{Blade mass } = \text{ blade number } \times 0.1452 \times R^{2.9158} & (1a) \\ \text{Hub mass } = 0.954 \times \left(\dfrac{total\ blade\ mass}{blade\ number}\right) + 5680.3 & (1b) \\ \text{Total pitch bearing mass } = 0.1295 \times total\ blade\ mass + 491.31 & (1c) \\ \text{Total pitch system mass } = (Total\ pitch\ bearing\ mass\ \times 1.328) + 555 & (1d) \\ \text{Nose cone mass } = 18.5 \times rotor\ diameter - 520.5 & (1e) \end{cases}$$

The blade mass equation (1a) is derived from WindPACT scaling study designs [S6, S7]. Since the HWT and conventional WT share the same rotor radius, the blade mass for the 2.5MW WT and HWT can be computed as 39169 kg. The hub mass equation (1b) is based on the revised scaling curve using hub mass as a function of a single blade mass [S6, S7]. For the 2.5MW HWT, the hub mass can be computed as 18136 kg. As indicated in (1c), the bearing mass is a function of the blade mass for all three blades, actuators and drivers are estimated as 32.8% of the bearing mass plus 555 kg in the NREL report [S6]. Then, the total pitch mechanism and bearing mass of 2.5WM WT and HWT is 7943 kg. With the formula (1e) derived from data in WindPACT drivetrain, the spinner (nose cone) mass of 2.5MW WT and HWT is 1329 kg.

2) Drive train and nacelle mass

The mass of drive train and nacelle includes that of the low-speed shaft, bearing, gearbox (and CVT for the HWT), mechanical brake and high-speed coupling, generator (VDM for the HWT), yaw drive and bearing, main-frame, hydraulic and cooling system, and nacelle cover. Each component of the drive train and nacelle mass can be determined by [S6, S7]:

$$\begin{cases} \text{Low}-\text{speed shaft mass} = 0.0142 \times rotor\ diameter^{2.888} & (2a) \\ \text{Bearing mass} = \left(rotor\ diameter \times \dfrac{8}{600} - 0.033\right) \times 0.0092 \times rotor\ diameter^{2.5} & (2b) \\ \text{Gearbox mass} = 88.29 \times low-speed\ shaft\ torque^{0.774} & (2c) \\ \text{Brake coupling mass} = \dfrac{1.9894 \times machine\ rating - 0.1141}{10} & (2d) \\ \text{Generator mass} = 10.51 \times machine\ rating^{0.9223} & (2e) \\ \text{Total yaw system mass} = 1.6 \times (0.0009 \times rotor\ diameter^{3.314}) & (2f) \\ \text{Total mainframe mass} = (1 + 0.125) \times (1.295 \times rotor\ diameter^{1.953}) & (2g) \\ \text{Hydraulic, cooling system mass} = 0.08 \times machine\ rating & (2h) \\ \text{Nacelle mass} = \dfrac{11.537 \times machine\ rating + 3849.7}{10} & (2i) \end{cases}$$

With the data collected from the WindPACT rotor study, low-speed shaft mass and main bearing mass can be estimated from rotor diameter, as indicated in (2a)-(2b). Thus, for the 2.5MW WT, the low-speed shaft mass is 8477.9kg. While for the 2.5MW hybrid wind turbine, to satisfy the increased shaft torque and the shear stress, the low-speed shaft diameter can be determined by [S5]:

$$\frac{T2}{T1} = \frac{(D^4 - d2^4)}{(D^4 - d1^4)}$$

where T2 and T1 are the maximum shaft torque of HWT and conventional WT, respectively; D represents the shaft outside diameter, and d2 and d1 are the shafts inside the diameter of HWT and conventional WT. For the 2.5MW WT and HWT, shaft outside diameter D is 130cm, and d1 of conventional WT is 127cm. Thus, d2 can be computed as 124.869cm by substituting T2 and T1 as 2.034 and 1.219 (the value in Fig.S2B). Since the material mass of the shaft is proportional to the square of the shaft diameter, the mass of the low-speed shaft is increased by 69.91% (computed from $\frac{(D^2-d2^2)}{(D^2-d1^2)}-1$).

According to the NREL report, the gearbox and generators are the most complicated components to estimate the mass because of the multiple available configurations. We choose the single-stage drive with the medium-speed generator, the gearbox mass of 2.5MW WT can be predicted through (2c). For the HWT, the CVT is embedded to change the mechanical energy transmission, and CVT transmissions are more lightweight and compact compared with standard gearbox transmission [S8, S9]. The mass of CVT is in the range of 0.722~0.911 kg/kW according to internal source of auto manufacture in China. As one of the critical parameters for auto business, such number is not available in public sources. For the standard 2.5MW HWT (with 3.3MW VDM), the capacity of CVT should be 3.3MW, thus the CVT mass of the 2.5MW HWT is in the range of 2383~3007kg, which leads to an increase of 16.94%~21.38% of the mass of gearbox and CVT.

The mass of mechanical brake, high-speed coupling, and associated components can be estimated from (2d), which is proportional to the machine rating (power capacity of a wind turbine). Thus, the mass of these parts for the 2.5MW WT and HWT are the same.

The mass of the generator with a single-stage drive with medium-speed generator configuration is indicated in (2e). For the HWT, we embedded VDM along with generator, and VDM offers higher power density than electric motor [S10, S11]. That is to say, VDM weights less compared with an electric generator with same power capacity, and the cost of VDM is estimated in the range of 1.428kg/kW~3.226kg/kW based on the power to weight ratio of air motors in [S12]. Thus, for the standard 2.5MW HWT (with 3.3MW VDM), the VDM mass is estimated as 4712kg~10645kg, which leads to an increase of 32.94%~74.41% mass to the generator and VDM.

The mass of Yaw system, which includes Yaw drive and bearing, can be estimated by (2f). Along with the assumption of the single-stage drive with medium-speed and permanent-magnet generator, the total mass of mainframe is the sum of mainframe mass and platform and railing mass and can be estimated by (2g). The mass of electrical connections can also be ignored as in [S6], and the mass of hydraulic and cooling systems can be estimated by (2h). The mass of nacelle cover is a function of machine rating in kW, and the nacelle cover mass can be estimated from (2i). Similar to [S6], the mass of control, safety system, and condition monitoring can also be ignored.

The mass composition of a conventional turbine and mass increase for the hybrid turbine is summarized in Table S1. As presented in the table, the new design of wind turbine could be 1388599.18kg~1454682.30kg, mainly because of the introduction of CVT and VDM, as well as the increased weight of the lower speed shaft. Such weight increase accounted for 10.30%~15.49% of the mass of turbine top (including rotor and generator), and the increased top mass only accounts for 1.04%~1.60% of the weight of the turbine.

Table S1.Component Mass of the 2.5 MW HWT and 2.5 MW WT.

Component	WT	Hybrid WT (Optimistic)		Hybrid WT (Pessmistic)	
	Mass(kg)	Increment	Mass (kg)	Increment	Mass (kg)
Rotor	**66578.42**		**66578.42**		**66578.42**
Blades	39169.19		39169.19		39169.19
Hub	18136.10		18136.10		18136.10
Pitch mchnsm & bearings	7943.62		7943.62		7943.62
Spinner, Nose Cone	1329.50		1329.50		1329.50
Drive train,nacelle	**59856.55**		**72877.96**		**79435.06**
Low speed shaft	8477.90	69.91%	14404.80	69.91%	14404.80
Bearings	1196.31		1196.31		1196.31
Gearbox/ **(Gearbox+CVT)**	14061.76	16.94%	16443.82	21.38%	17068.16
Mech brake, HS cpling etc	497.34		497.34		497.34
Generator/**(Generator+VDM)**	14306.15	32.94%	19018.60	74.41%	24951.36
Variable spd eletronics	0.00				0.00
Yaw drive & bearing	6114.52		6114.52		6114.52
Main frame	11733.36		11733.36		11733.36
Electrical connections	0.00		0.00		0.00
Hydraulic, Cooling system	200.00		200.00		200.00
Nacelle cover	3269.22		3269.22		3269.22
Control, Safety System, Monitoring	**0.00**		**0.00**		**0.00**
Top Mass	**126434.97**	10.30%	**139456.38**	15.49%	**146013.48**
Increased of top mass compared to the total weight (%)		**1.04%**		**1.60%**	
Strengthen of tower (%)		**10.59%**		**15.86%**	
Strengthen of foundation (%)		**10.56%**		**15.82%**	
Note: The tower mass for conventional WT is 1129526 kg, and the total mass is 1255960.97kg.					

3) Tower mass

For the conventional WT, the tower mass is a function of the swept area and hub height, and can be estimated using the baseline tower mass scaling relationship in [S3], i.e.,

$$\text{Tower mass} = 1.6 \times (swept\ area \times hub\ height) - 1414 \tag{3}$$

As the weight for the nacelle increases with the HWT design, the tower needs further strengthen to cope with the additional pressure incurred. According to [S5], the increase of top mass needs to change the inner diameter of the tower, i.e.,

$$\frac{P2}{P1} = \frac{(D^4 - d2^4)}{(D^4 - d1^4)}$$

where P2 and P1 is the top mass of the tower for the HWT and the conventional WT; *D* represents the tower outside diameter for a 2.5MW WT; *D* is 350 cm; *d2* and *d1* are the tower inner diameter of the HWT and conventional WT, and *d1* is 343 cm. By instituting P2 and P1 with the top mass in Table S1, we can get that the upper bound of the tower inner diameter for HWT is 342.25cm and the lower bound of the tower inner diameter for HWT is 341.87cm. Thus, the tower mass increases by 10.59%~15.86% ($\frac{(D^2-d2^2)}{(D^2-d1^2)}$-1), as compared with the counterparts in the conventional turbine.

Given the weight increase of nacelle for the new design and subsequent strength of the tower, the foundation needs to be strengthened by 10.56%~15.82%, which will also be reflected in the cost analysis. The implications on overall costs will be presented in section 9. As will be indicated, the cost increment for strengthening tower and foundation contribute to less than 2.04%~3.01% of the total costs, as these parts are relatively less expansive compared with rotor and generators.

We note that we only consider here the modification based on the existing mainstream turbine, the integrated design to optimize the parameters could also improve the overall performance and reduce total costs.

S4. Engineering Model of Torque and Pressure for HWT

In this section, we formulate the engineering model of the torque and pressure of VDM. Such engineering model motivates the control solution of CVT and VDM to determine their reference power point during practical operation. Moreover, we demonstrate that the HWT can keep a high-efficiency operation of CVT and VDM under a wide range of wind speeds. Thus, we can formulate the internal power flow and scheduling models of the HWT by using constant efficiency parameters and neglecting the detailed engineering characteristics. Such constant efficiency character will benefit the formulation of the scheduling model of HWT in section S7 and the analysis of the dispatchability it imposed on power systems in section S8. In this regard, we first analyze the torque balance of VDM, followed by the pressure balance of VDM. Then, we drive the control solution and illustrate the high-efficiency feature of the HWT.

1) VDM wobble plate torque analysis

As indicated in Figure S3, we represent the polar angular position of Piston A1 as ς and define the effective radius of the wobble plate as R^D, which measures the distance between the centers of the wobble shaft and piston shaft. The piston force at position ς is represented by F_ς^P and is decomposed to the tangential force component F_ς^D, which is perpendicular to the shaft of the wobble plate, and the orthogonal component F_ς^N, which is perpendicular to the wobble plate.

Take compression process as an example, in the closed compression phase, the volume V_ζ of the air chamber at position ζ is calculated by:

$$V_\zeta = S(H + R^D \sin\delta \cos\zeta) \tag{4}$$

where S represents the area of the piston head. Then, the relative compression ratio γ_ζ^c at the position ζ can be calculated by:

$$\gamma_\zeta^c = \frac{(H+R^D \sin\delta)}{(H+R^D \sin\delta \cos\zeta)} \tag{5}$$

Correspondingly, the piston force F_ζ^P and its tangential force component F_ζ^D can be respectively determined by:

$$F_\zeta^P = \gamma_\zeta^c p^0 S \tag{6}$$

$$F_\zeta^D = F_\zeta^P \tan\delta \tag{7}$$

where p^0 represents the atmospheric pressure. The torque on the wobble plate is then formulated as:

$$T_{\zeta,1} = F_\zeta^D R_\zeta = \frac{H+R^D \sin\delta}{H+R^D \sin\delta \cos\zeta} p^0 S R^D \tan\delta \sin\zeta \tag{8}$$

where R_ζ represents the effective arm on position ζ.

Follow a similar calculation process that applies to the open ejection phase and replace the relative compression ratio with the constant final compression ratio. The torque on the wobble plate is expressed by:

$$T_{\zeta,2} = p^{ASU} S R^D \, tan \, \delta \, sin \, \zeta \tag{9}$$

where p^{ASU} represents the air pressure in the ASU.

For the open suction phase, the torque from the air friction is negligible. In this respect, the torque from pistons to the wobble plate, T^D, is the expected torque multiplied by the total number of pistons can be formulated as:

$$T^D = n^{cy} T^{cy} = n^{cy} \left(\int_0^{\zeta_1^{cy}} T_{\zeta,1} d\zeta + \int_{\zeta_1^{cy}}^{\zeta_1^{cy}+\zeta_2^{cy}} T_{\zeta,2} d\zeta + \int_{\zeta_1^{cy}+\zeta_2^{cy}}^{2\pi} 0 d\zeta \right) \tag{10}$$

where n^{cy} is the total number of pistons or cylinders; ζ_1^{cy} and ζ_1^{cy} represent the angles for closed compression and open ejection, respectively; T^{cy} is the expected torque from one single piston, and is calculated by the integration of the piston torque through 2π of the wobble plate. It should be noted that the integration in (10) will eliminate the angular position variable ζ.

According to the fundamentals of fluid dynamics, if the air pressure is predetermined, a single optimal rotation speed of the fluid machine can be calculated. In this regard, the optimal rotation speed is determined as $\Omega_{p^{ASU}}^{V,opt}$ concerning the air pressure of ASU. To compromise between power output and efficiency, the optimal rotation speed of VDM is selected between the maximum power point and the maximum efficiency point. By considering the frictional effect on the torque imposed by the flow rated of the fluid (air), we introduce a discounting factor c_2 in the model, then the VDM power (both charging or discharging) can be expressed as:

$$P^V = c_2 T^D \Omega_{p^{ASU}}^{opt} = f_D(H, \delta) \tag{11}$$

where $f_D(\cdot)$ is the function of the control pair (H, δ) of the VDM.

2) VDM outlet pressure analysis

In the compression mode, the pressure change occurs only in the closed compression phase. According to Equation (4), the initial volume V1 and final volume V2 are calculated by:

$$V_1 = S(H + R^D \sin\delta) \tag{12}$$

$$V_2 = S\left(H + R^D \sin\delta \cos\zeta_1^{cy}\right) \tag{13}$$

To model the limit of the wobble angle and physical inference between the piston head and cylinder bottom, we introduce the following constraint:

$$\delta \in \left(-\frac{\pi}{4}, \frac{\pi}{4}\right),\ H > R^D \sin\delta \tag{14}$$

The compression ratio is then calculated by:

$$\gamma^{V_c} = \frac{V_1}{V_2} = f_\gamma(H, \delta) \tag{15}$$

where $f_r(\cdot)$ is the function of the control pair (H, δ) of the VDM since the close compression angle ζ_1^{cy} is constant.

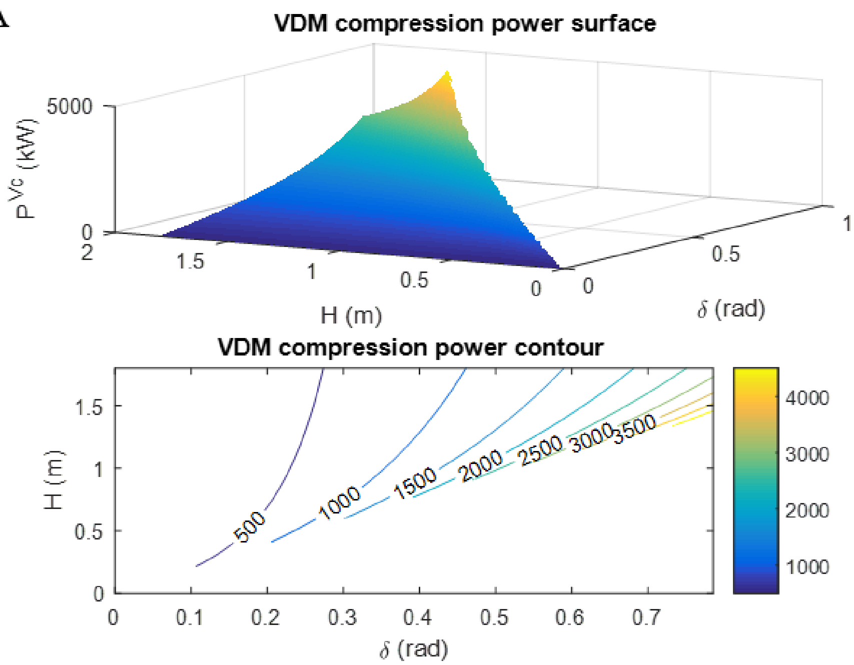
Equation (11) and Equation (15) indicate that the VDM control pair (H, δ) serves as the control variable to adjust both the VDM power and its compression ratio (also expansion ratio). Since we have two equations for two variables (H, δ), the reference of H and δ can be obtained by jointly solving the equations.

3) Control solution of VDM

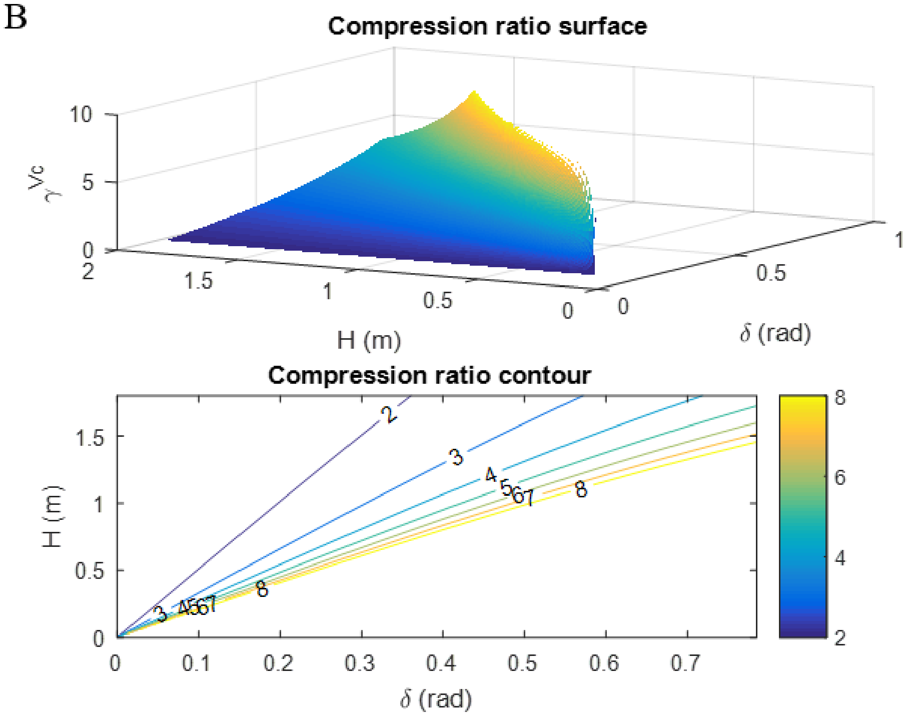
We use the numerical method to solve questions (11) and (15), whose analytical solution is hard to obtain due to their integration terms. The 3D surfaces and their contours on the “wobble angle-NPD" plane/domain for the compression ratio and VDM power are plotted in Figure S5(A) and Figure S5(B), respectively, in which the x-axis represents δ and the y-axis H.

An overlap of both contours in Figure S5(C) gives the mesh grid and intersection points of the compression ratio and power. Three points are plotted to explain the dynamic working states of the VDM. While the compression ratio is at R2 and VDM power is at L1, the operational point of VDM is at Point a. If the compression ratio decreases from R2 to R1, according to the tank pressure decrease, and the VDM power is constant, the operational point will move to Point B through Line ab. If the tank pressure is constant, but the VDM power is increased from L1 to L2, the operating point moves to Point c through Line ac. Those movements demonstrate the dynamic working states of the VDM, and the references of the wobble angle and NPD are calculated by the corresponding values on the x and y-axes.

A



B



C

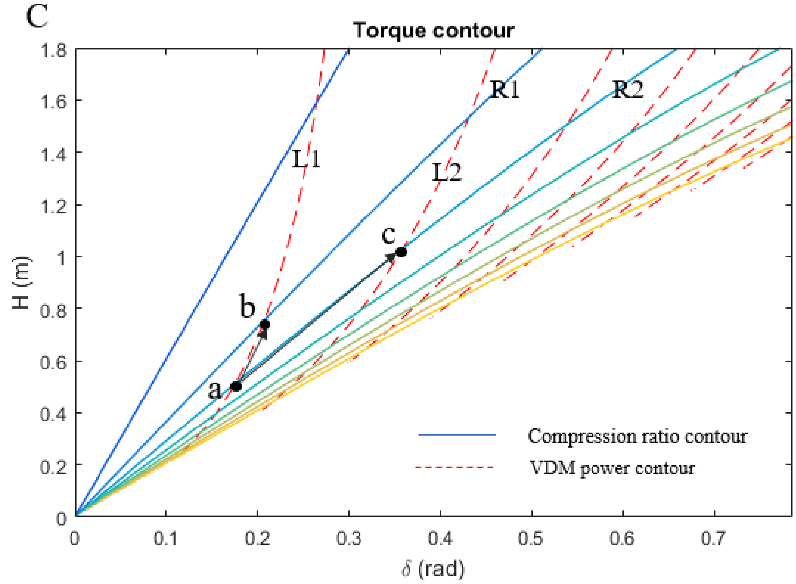


Figure S5. The graphic solution for operation and regulation of VDM. (A) VDM compression power surface and power contour, concerning control variables of VDM, i.e., the wobble angle (***δ***) and neutral piston displacement (***H***). (B)VDM compression ratio surface and contour with respect to the wobble angle (***δ***) and neutral piston displacement (***H***). (C) The unique solution of VDM control parameters under the desired power and compression ratio. The contour's overlap graphic solution shows the unique solution and smooth operation surface of VDM.

In summary, with the control of the wobble angle and neutral piston displacement of VDM, we can continuously regulate the power of VDM in different wind conditions and power demand.

4) *Efficiency on variations of wind conditions*

As indicated above, we can regulate the power of VDM by adjusting the control pair of the wobble angle (δ) and neutral piston displacement (H). Then, the efficiency discount during different wind conditions, i.e., different VDM charging power and discharging power, should be considered. Here, we will demonstrate that the variation of VDM power has little effect on the charging and discharging efficiency of VDM.

Typically, the performance of conventional compressors and expanders could vary with the charging and discharging power. The efficiency of compressor and expander can be high at the rated power point, while the efficiency decreases a lot along with the variation of charging and discharging power of compressor and expander. This is the so-called part-load efficiency issues that occurred in the compressor and expander of the gas turbine and compressed air energy storage plant, as indicated in Figure S6 and Figure S7.

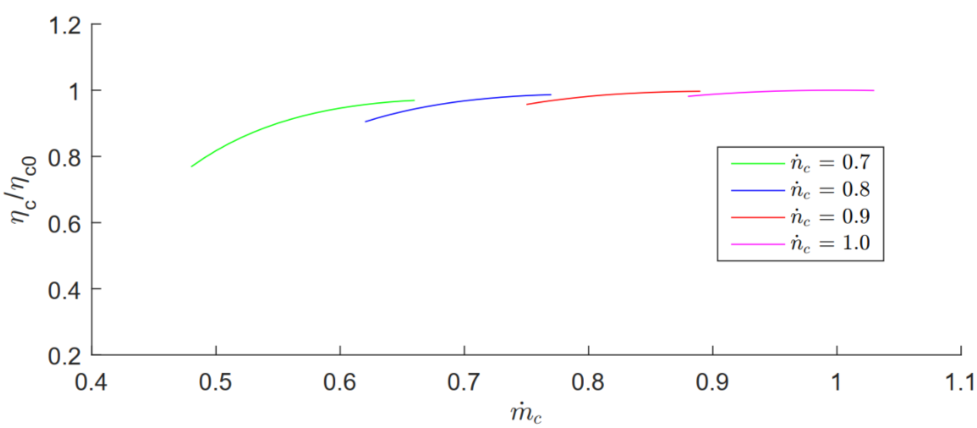


Figure S6. An example of the part-load efficiency behavior of air compressor.

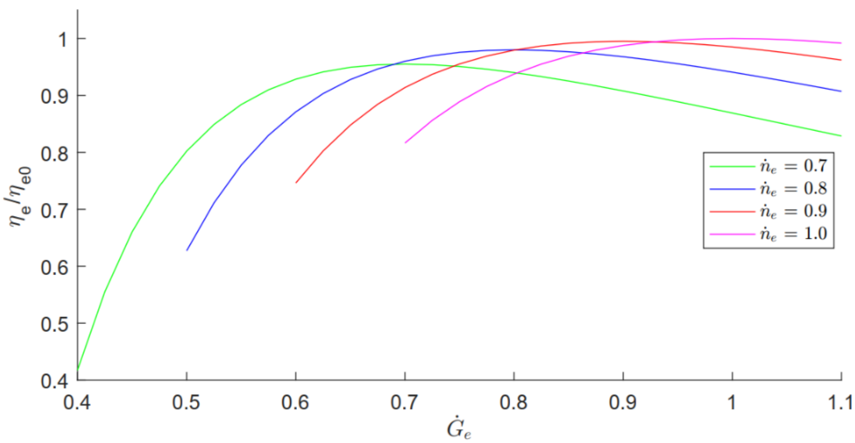


Figure S7. An example of the part-load efficiency behavior of air expander.

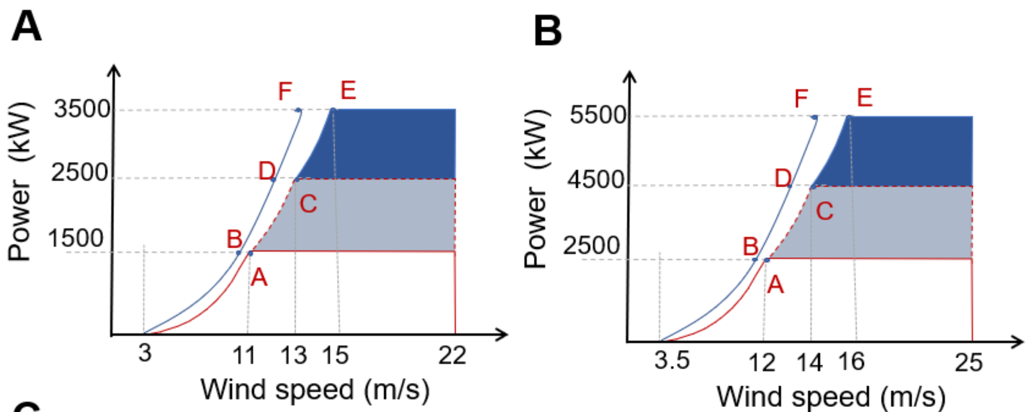
In Figure S6, n_c is the rotation speed of air compressor, m_c is the mass flow rates of air (corresponding to charging power), and subscript 0 is the rated value at rated operation point. In Figure S7, n_e is the rotation speed of air expander, m_e is the mass flow rates of air (corresponding to discharging power), and subscript 0 is the rated value at rated operation point. The fundamental reason for the part-load efficiency of such rotational machines is the mismatch between the rated power capacity and variable real-time compression and expansion power. It valid for the HWT if one only borrows the VDM from other industries without any reasonable modification.

Nevertheless, as indicated in Figure S1(A), and the control solution in section S4-3), we incorporated another control freedom for VDM, i.e., the neutral piston displacement (H), to overcome the part-load issue. With the adjustment of the neutral piston displacement, the rated capacity of VDM can be adjusted regarding the variation of compression or expansion power. Thus, accompanied with the original control variable in the VDM of automobile field, i.e., the wobble angle (δ), the control pair of wobble angle and piston displacement, can guarantee the relatively constant charging efficiency of 80% and discharging efficiency of 80% under a broad range of compression and expansion power, i.e., under a wide range of wind speeds and load demands. More detailed parameter settings for the HWT is indicated in section 10.

S5. Notes on VDM *Sizing and Energy Density*

Optimal sizing of the HWT is important to determine proper wind turbine parameters, i.e., power capacity and energy capacity. We offer several power capacity choices and decouple the sizing of energy capacity with power capacity. Thus, the size of the air tank and thermal tank can be optimized according to the available conditions. For the power capacity, we offer several standard designs for 1.5MW and 2.5MW wind turbines, as indicated in Fig.S9, while the energy capacity is illustrated in Table S2.

As indicated in Fig. S8(A), the rated charging power for the VDM of 1.5MW turbine is 3.5MW (Point E). It guarantees to produce ~1.5MW rated power (considering round-trip efficiency) even if there is no wind under the condition that enough energy has stored. Besides, we also provide another kind of design with different VDM power capacities (Point C). As indicated in Fig. S8(B), for the 2.5MW wind turbine used in the US cases, the rated VDM power is 5.5 MW, which can guarantee to provide ~2.5MW rated power for the periods when there is no wind. Similar to 1.5MW wind turbine, we also provide other designs to consider different VDM power capacity. Last but not least, we can also shift the power curve for the proposed HWT to extend its application in other wind conditions, as in Fig. S8(C), and the term 'E' in "WT-E", "VDM1-E", and "VDM2-E" represents the extension of the wind blade.



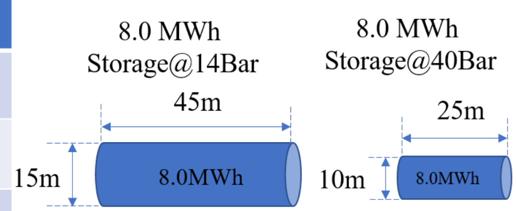
C

Point	WT Type	Point	WT Type	Point	WT Type
A	WT	C	VDM1	E	VDM2
B	WT-E	D	VDM1-E	F	VDM2-E

Figure S8. Parameter settings and operation points explanation for the HWT with 1.5MW and 2.5 MW rated power capacity.

Table S2. The energy density of the mechanical add-on in HWT.

Pressure (Bar)	14	30	40
Energy (kWh)	1.03	2.83	4.10
Pressure (Bar)	50	60	70
Energy (kWh)	5.43	6.82	8.26



As indicated in Table S2, the size of the storage tank is determined by the maximum air pressure of the air tank. For the standard case, the energy density is 1kWh/m^3. For the widely-used steel-pipeline in West-East Gas Transmission of China, its maximal pressure can reach 120 Bar. In practical engineering, we usually choose higher storage air pressure to save the volume of air tank. Assuming that we choose a 60 Bar air storage tank, which is generally lower than the maximum air pressure of the aforementioned Huntorf and McIntosh plants. For the 1.5MW hybrid

WT (the type VDM2 in Fig.S8), the available kinetic power is 3.5 MW if all these kinetic energies are stored (no power output to the power grid) at 20m/s wind speed. Then, the volume of the storage tank can be ~2,000 m^3 and ~7,600 m^3 for 4 hours and 12 hours, respectively, and these two storage volumes can be realized with a matrix-form arrangement of 4 steel pipeline based air strorage tanks, with each has the length of 10 m and radius of 4 m and 7.8 m, respectively.

Accompanying with Fig.1 in the manuscript, we illustrated the sensitivity analysis of the wind electricity generation capability of the HWT with different power capacity designs and a fixed 12-hour energy storage capacity in Fig.S9.

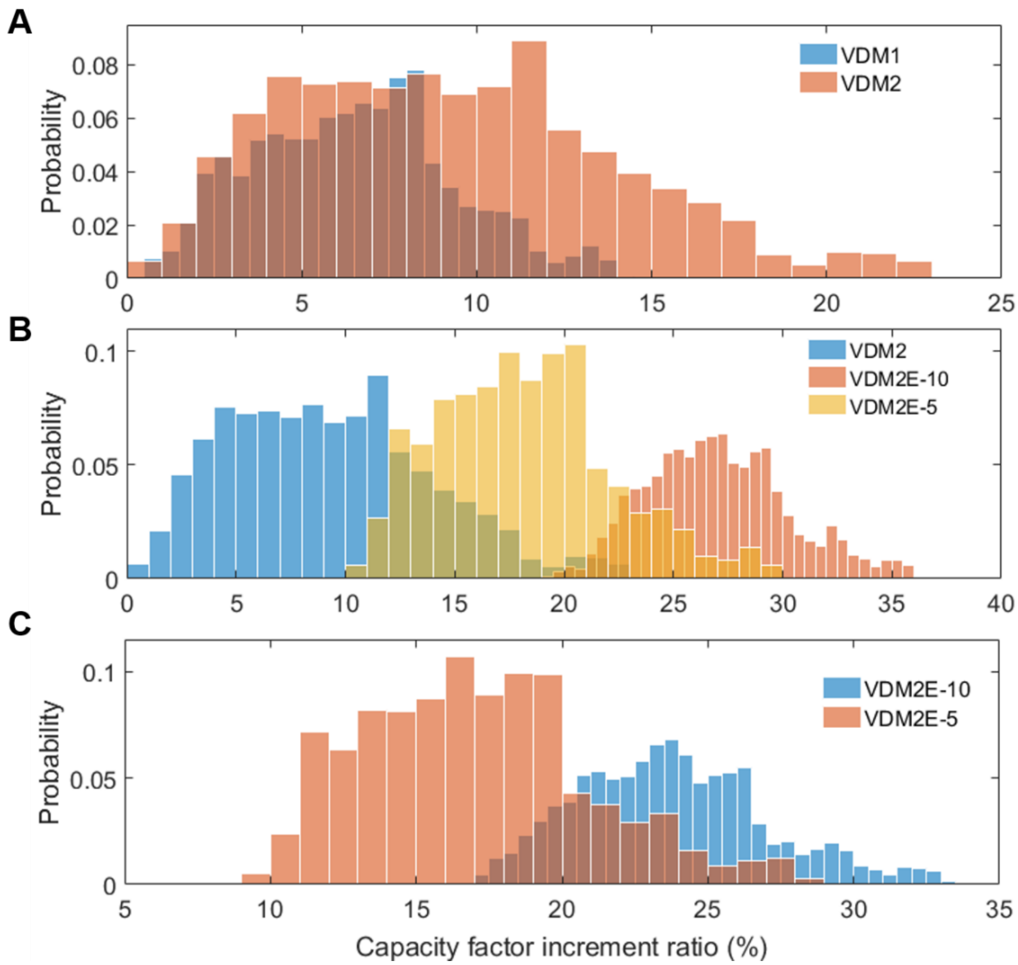


Figure S9. Sensitivity analysis of the wind electricity generation capability of the HWT. (A) Capacity factor increment of HWT with respect to WT regarding the power capacity of VDM. The 1.5MW HWT, equipped with mechanical storage of a 2MW VDM, outperforms 1MW VDM. (B) Capacity factor increment of HWT with respect to WT regarding different blade radius for a 2 MW VDM capacity. With a 5% blade radius increment, the CF increment can reach 10%-30%, and with a 10% blade radius increment, the CF increment is in the range 20%-37%. (C) Capacity factor increment of the HWT with respect to a WT with the same blade length increment. With 5% radius increment, the CF increment is in the range of 9%-28%, and with a 10% radius increment, the CF increment reaches 17.5%-34%.

S6. Notes on Annual Wind Speed and Wind Energy Distribution

As indicated previously, the proposed HWT is not feasible for all wind conditions because the charging process is activated when the wind speed is higher than the rated speed. Nevertheless, the proposed HWT can find a place with proper wind speed distribution, and such kind of condition can be regarded as a criterion for the location and sizing issue of the HWT indicated in section 5. As illustrated in Fig.2, many regions in both China and the U.S. will gain benefits from the use of HWT.

1) Annual wind speed and kinetic energy distribution

We choose two typical locations in the Western Inner Mongolia System to illustrate the impact of wind speed distribution on the feasibility of installing the HWT, and more details about this system can be found in section 8.

As indicated in Figure S10, the hour percentages of wind speed higher than the rated speed are 7.28% and 27.16% for location 1 and location 2, respectively. Moreover, the kinetic energy percentages which can be recycled in the HWT design are 13.08% and 34.04% for location 1 and location 2, respectively.

Location 1 may not be a proper location for HWT, because the duration of wind speed higher than the rated speed of a 1.5MW wind turbine(11m/s) is too short. Nevertheless, location 2 is ideal for installing HWT. Because the duration of wind speed larger than rated speed is long which stands for abundant kinetic energy available.

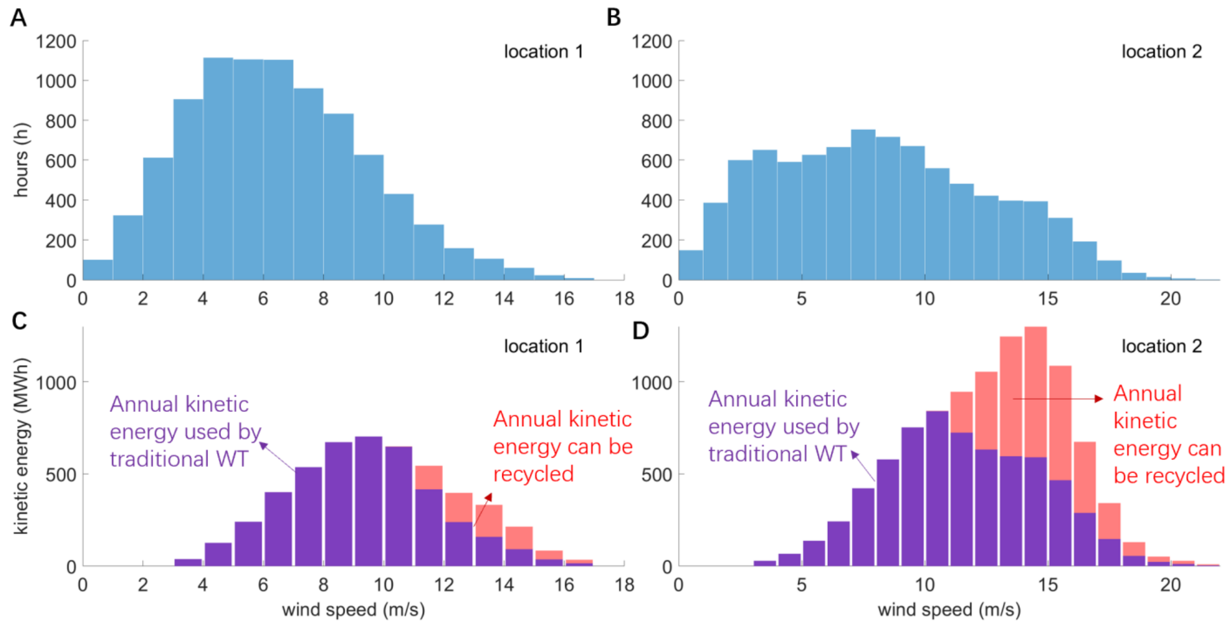


Figure S40. Annual wind speed and kinetic energy distribution of two sample locations in China. (A) Annual wind speed distribution for location 1 in wind-poor areas. (B) Annual wind speed distribution for location 2 in wind-rich areas. (C) Annual kinetic energy distribution for location 1, including the kinetic energy used by the **conventional** wind turbine and the kinetic energy**,** can be recycled by the proposed **HWT**. (D) Annual kinetic energy distribution for location 2.

2) Benefits offered by dispatch-ability

As highlighted in the manuscript, the main purpose of such a hybrid design is to enable dispatch-ability to wind power. For the West Inner Mongolia case investigated in Fig.4 of the manuscript, the maximum penetration ratio of wind power can be increased by 47.62% if HWTs are adopted. Moreover, with 23GW HWTs, the carbon emission reduction ratio can reach that of 62GW conventional wind turbines.

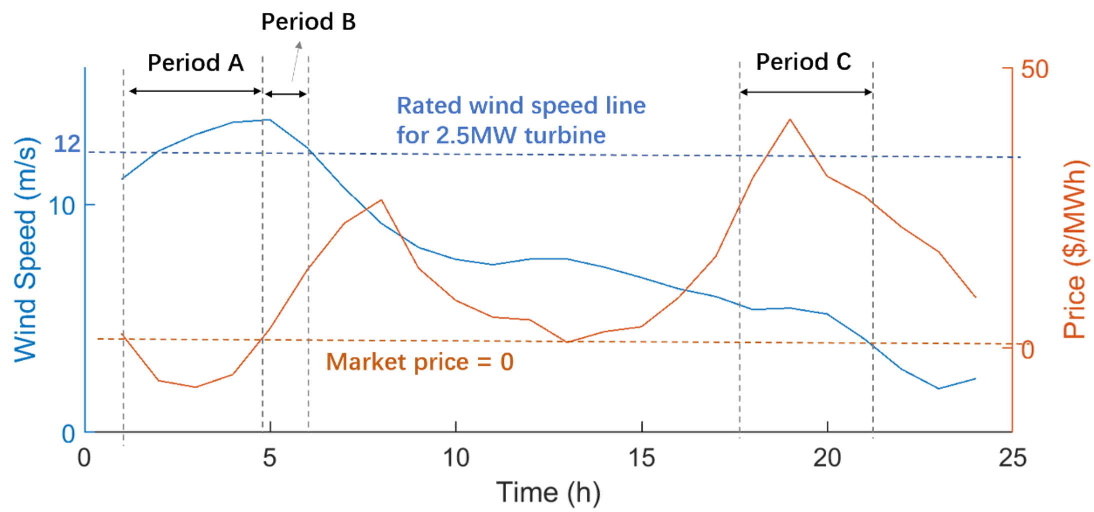


Figure S51. Comparison of market behavior of conventional wind turbines and HWTs during different wind conditions and market price scenarios with the CAISO market in the U.S.

The HWT can not only capture the additional energy but can decouple the generated power and wind speed with the embedded storage. **The embedded storage in the HWT does not only function during time periods with excessive wind energy, but can also operate during time periods with lower wind speeds depending on market conditions.**

Considering the CAISO example illustrated in Fig.S11, during **Period A,** the market price is negative, the wind speed is around the rated wind speed, i.e., 12 m/s, for the 2.5MW wind turbine. Because of the negative price in Period A, conventional wind turbine usually curtails the available kinetic energy due to the lack of dispatchability, while the HWT can charge the embedded mechanical storage with available kinetic energy both for the less than rated speed periods and above than rated speed periods, and then shift the stored energy to periods with positive electricity price. For **Period B,** the market price is positive but low, and the optimal choice of a conventional wind turbine is to sell the wind power to the grid while the proposed HWT can shift power in Period B to **Period C** which has a higher price than that in Period B. These benefits are the true value of the flexibility of the proposed design.

Last but not least, for the case in Fig.S11, we only compared the behavior of conventional wind turbines and HWTs in the energy market. Besides, the flexibility enhanced by HWT can also provide ancillary service for the grid. It brings extra economic benefits to the owner of wind farms and operational benefits to the owner of power grids, as we illustrated in the Inner Mongolia case in Fig 4 in the manuscript.

S7. Scheduling Models of the HWT

With the mechanical add-ons to the HWT, to maximize the electricity yield, it is important to optimally determine the internal energy exchange between rotor, generator, and the added mechanical storage. It is also important in a market environment to do this to maximize the profit of the wind generators. In this section, the internal energy flow and the control model are described first, followed by the models employed to maximize the electricity yield and revenue for a market application.

1) *Internal power flow model of HWT*

The internal power flow of the HWT is illustrated in Fig.S12. The kinetic energy captured by the blades is used to either generate electricity or drive the VDM. Electricity can be generated from either the kinetic energy supplied directly by the rotor or with energy stored via the VDM. The embedded mechanical add-ons can function as a kinetic energy buffer. The surplus kinetic energy stored in the TES and ASU can be released through the discharge of VDM if necessary at other time periods. The modeling formulations below represent the internal power balance and relevant constraints for different subcomponents of the HWT.

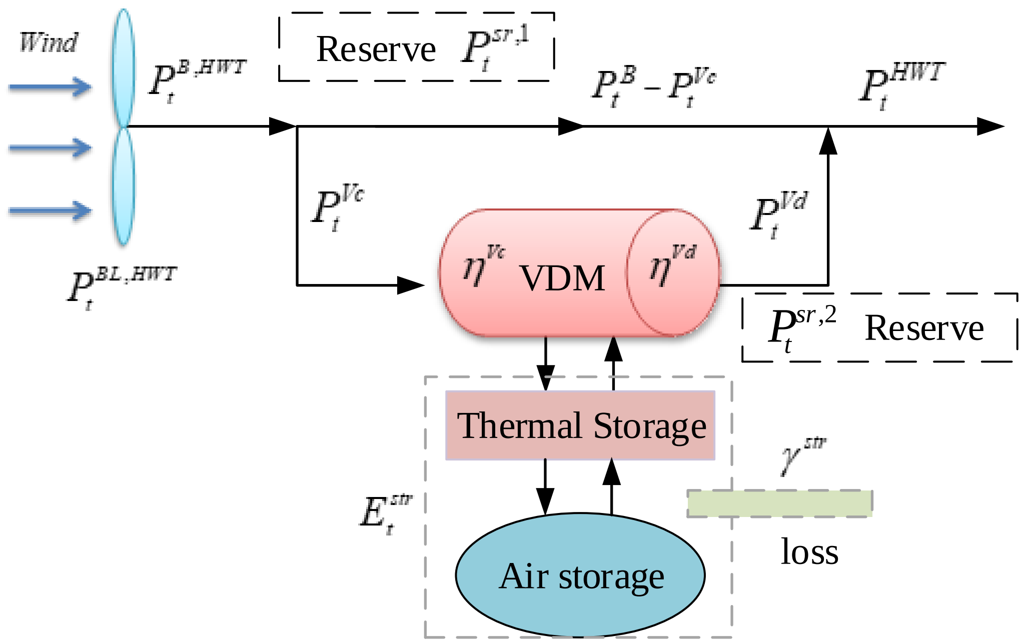


Figure S12. Internal power flow of the HWT.

The electric power output of the HWT is formulated as:

$$P_t^{HWT} = P_t^{B,HWT} + P_t^{Vd} - P_t^{Vc}, \forall t \tag{16}$$

$$P_t^{B,HWT} \le P_t^{B,Curve}, \forall t \tag{17}$$

$$P_t^{HWT} \le P_{rated}^{WT}, \forall t \tag{18}$$

where P_t^{HWT} represents the power output of the HWT, $P_t^{B,HWT}$ is the kinetic energy captured by the blades of the turbine, P_t^{Vc} is the compression power of the VDM, P_t^{Vd} denotes the expansion power of VDM, $P_t^{B,Curve}$ is the maximum kinetic power defined by the power curve in Fig.1B, and P_{rated}^{WT} is the rated electric power of the HWT. The term $P_t^{Vc}P_t^{Vd}$ should equal zero at any time, either in the compression mode ($P_t^{Vc} > 0, P_t^{Vd} = 0$) or in the expansion mode ($P_t^{Vd} > 0, P_t^{Vc} = 0$).

The kinetic energy stored in the embedded TES and ASU of the HWT is formulated as:

$$E_{t+1}^{str} = (1 - \gamma^{str})E_t^{str} + \eta^{Vc}P_t^{Vc}\Delta t - \frac{P_t^{Vd}\Delta t}{\eta^{Vd}}, \forall t \tag{19}$$

$$E_{\min}^{str} \le E_t^{str} \le E_{\max}^{str}, \forall t \tag{20}$$

$$0 = P_{\min}^{Vc} \leq P_t^{Vc} \leq P_{\max}^{Vc} = P_{rated}^{VDM}, \forall t \tag{21}$$

$$0 = P_{\min}^{Vd} \leq P_t^{Vd} \leq P_{\max}^{Vd} = \eta^{Vd} P_{rated}^{VDM}, \forall t \tag{22}$$

where E_t^{str} represents the mechanical energy stored at t, γ^{str} represents the coefficient for self-discharge, η^{Vc} denotes the compression efficiency of the VDM, η^{Vd} is the expansion efficiency, Δt is the time interval between two consecutive time periods, $E_{\min}^{str}$ and $E_{\max}^{str}$ are the minimum and maximum volume of mechanical energy stored, $P_{\min}^{Vc}$ and $P_{\max}^{Vc}$ are the lower and upper bound of the VDM charging power, $P_{\min}^{Vd}$ and $P_{\max}^{Vd}$ are the lower and upper bounds of the VDM discharging power, and P_{rated}^{VDM} is the rated power capacity of the VDM. It should be noted that $P_{\max}^{Vd}$ and $P_{\max}^{Vc}$ are not necessarily equal, as indicated in Equations (21) and (22).

2) Electricity generation maximization model

With the detailed description of the internal power exchange of the HWT and the corresponding limitations, we can maximize the total electricity yield with changing wind speeds as mathematical formulation as follows:

$$\begin{gathered} \text{Max } \frac{1}{8760 \times P_{rated}^{WT}} \sum_{t=1}^{8760} P_t^{HWT} \Delta t \\ subject\ to \ \ \text{internal power flow constraints for HWT defined in } (16) - (22) \end{gathered} \tag{23}$$

3) Optimal scheduling model to maximize the revenue in wholesale markets

Considering the market participation behavior of current wind farms, we assumed that the wind farm with HWTs acts as a price-taker in the electricity market.

In a power market environment, revenue from a wholesale electricity market depends not only on the total electricity generated but also on the price when wind power is delivered to the market. Further considering the change of market clearing price in addition to the changing wind speed, the model to maximize the profit of proposed HWT in the electricity market is summarized as follows:

$$\text{Max } \sum_{t=1}^{8760} \lambda_t^E P_t^{HWT} \Delta t \quad (24)$$
$$subject\ to\ \text{ internal power flow constraints of HWT defined in } (16) - (22)$$

where λ_t^E denotes the electricity market price in the market region. Wholesale electricity market prices can change significantly over different regions. For all six US power markets investigated in the main text, we selected one reference nodal price as representative for each market. The detailed reference nodal price selection method is documented in [S15]. This reference node includes *NIPS.MICHCP12* for the PJM market, *LONG-LAKE-PHOENIX* for the NYISO market, NEISO-LBMP-Reference for the ISO-NE market, ALTW.OTTUMW1 for the MISO market, HB-HOUSTON for the ERCOT market, and 0096WD_7_N001 for the CAISO market.

S8. Unit Commitment Model for Optimally Operation of Power Systems Incorporating HWT

In this section, we first propose the unit commitment model for the operation power systems incorporating large-scale wind power. Then, we elaborate the used tested power systems, i.e., *Western Inner Mongolia (WIM)* Power *System*.

1) Unit Commitment Model

With the embedded storage capabilities, the HWT can provide critical flexibility for system operation. To optimally dispatch the system in the presence of the proposed HWT, we developed a novel unit commitment model. This model takes regular thermal power plants, combined heat and power (CHP) units, conventional wind farms as well as proposed HWTs into consideration. The objective function is designed to minimize system operation cost (fuel cost and start-up cost) as follows:

$$\min \quad f = \sum_{t=1}^{N_T} \sum_{i=1}^{N_c} C_{i,t}^p + \sum_{t=1}^{N_T} \sum_{i=1}^{N_c} C_{i,t}^c + \sum_{t=1}^{N_T-1} \sum_{i=1}^{N_c} S_{i,t}^c + \sum_{t=1}^{N_T-1} \sum_{i=1}^{N_p} S_{i,t}^p \quad (25)$$

where N_T represents the number of time periods, N_p and N_c denote the number of conventional thermal power plants and CHPs, respectively. $C_{i,t}^c$ and $S_{i,t}^c$ are the fuel cost and start-up cost for CHPs. The fuel costs for power plants $C_{i,t}^p$ depend linearly on fuel consumption. $S_{i,t}^p$ represents the start-up cost for conventional power plants.

Constraints of the conventional unit commitment model involve power balance, system reserve requirements, flexibility requirements for conventional thermal and CHP units. The full set of the equation for unit commitment problem can be found in [S16]. With the addition of HWTs, we need to reformulate several critical constraints. The system power balance constraint is formulated as:

$$\sum_{i=1}^{N_p} p_{i,t}^e + \sum_{i=1}^{N_c} p_{i,t}^c + \sum_{i=1}^{N_w} p_{i,t}^{HWT} + \sum_{i=1}^{N_b} p_{i,t}^b = P_t, \forall t \tag{26}$$

where P_t is the system power demand at time *t*, $p_{i,t}^b$ is the power imported from *i*th neighboring regions at time *t*, N_w is the number of HWTs.

The system reserve constraint is formulated as:

$$\sum_{i=1}^{N_p} u_{i,t}^e \bar{p}_i^e + \sum_{i=1}^{N_c} \hat{p}_{it}^c + \sum_{i=1}^{N_b} p_{i,t}^b \geq P_t + R_t^S - \sum_{i=1}^{N_w} R_{i,t}^W, \forall t \tag{27}$$

where $u_{i,t}^e$ is the binary variable including the on/off status of thermal plant *i* at time *t*, $\bar{p}_i^e$ is the nameplate capacity for the *i*th thermal unit, $\hat{p}_{i,t}^c$ indicates the maximum possible power output for the *i*th CHP unit at time *t*, R_t^S is the required system reserve margin at time *t*, $R_{i,t}^W$ is the reserve capacity can be contributed from the HWT at time *t*. As indicated in Fig.S3, the reserve capacity of the HWT, $R_{i,t}^W$, can be derived from two sources: under-utilized power could be captured by the blades, $P_t^{sr,1}$, and the potential discharging capacity of the VDM, $P_t^{sr,2}$. These two power reserve capacities are limited by the operation status of the HWT and can be formulated as:

$$R_t^W = P_t^{sr,1} + P_t^{sr,2}, \forall t \tag{28}$$

$$0 \leq P_t^{HWT} + R_t^W \leq P_{rated}^{WT}, \forall t \tag{29}$$

$$0 \leq P_t^{sr,1} \leq P_t^{B,Curve} - P_t^{B,HWT}, \forall t \tag{30}$$

$$0 \leq P_t^{sr,2} \leq [(1-\gamma^{str})E_t^{str} - E_{\min}^{str}]\eta^{Vd}/\Delta t - P_t^{Vd}, \forall t \tag{31}$$

The modified unit commitment model is employed to simulate the West Inner Mongolia power systems with an hourly time resolution over an entire year. The simulation is conducted on Harvard Odyssey Server, with the solver of Gurobi 8.0.1. Detailed data and mathematical formulations are available from the authors.

2) Detailed Descriptions of Western Inner Mongolia System

We use the above UC model to justify the effectiveness of the HWT in WIM, which is a representative example of the three northern regions where China's wind power potentials are highest. WIM has experienced a rapid expansion of capacities for both wind power and CHP over the past decade. The capacity of wind power in WIM increased from 0.04 GW in 2003 to 10.85 GW in 2013, corresponding to an annual growth rate of 74%. CHP capacity in the region grew from 4.5 GW in 2003 to 26.1 GW in 2013, quintupling over the same time period. In 2013, the generating capacity of the WIM power system totaled 48.8 GW, with 22.2% from wind and 53.6% from CHP units with a lower contribution from conventional coal units (20.4%), natural gas (2.1%) and hydro (1.7%). The fractions of wind power curtailed in 2012 and 2013 were 26.0% and 12.2%, respectively. Electricity produced in the WIM system primarily serves local demand, with a small fraction exported to the larger North China Gird (approximately 16% of generation). Planning documents project that demand for electricity for WIM will increase from 155 TW h in 2012 to 351 TW h in 2020, based on assumed annual average growth rates of 10.2% from 2012 to 2015 and 9.3% from 2016 to 2020. The capacity of wind power in the WIM region is projected to increase from the 2013 level of 10.9 GW to 20 GW by 2015, reaching 40

GW by 2020. At the same time, investment in CHP plants is projected to continue to meet the increasing demand for both hot water and electricity. This trajectory poses a severe challenge to integrating the increasing supply of wind power in the future WIM power system.

S9. Capital Cost Breakdown of HWT

This section evaluates the cost increase required for the HWT as compared with the conventional turbine. For the conventional turbine, the total investment cost and detailed breakdowns are based on NREL statistics from [S6] and [S17]. According to the wind energy review of NREL in 2017 [S17], the per kW capital cost of the wind turbine is $1,610, and a standard 2.5MW wind turbine costs $4,025. Based on the capital cost breakdown of wind turbine released by NREL [S6], we summarized each term of the conventional 2.5MW wind turbine in Table S2. The cost increment for the HWT is detailed as follows.

The HWT allows for capturing additional kinetic energy when the wind speed is higher than the rated speed, which leads to an increase in both the rotation speed and the torque imposed on the shaft. Comparing a 2.5 MW HWT to a conventional WT at the same rated capacity, the HWT increases the maximum shaft torque by 66.86% (Fig.S4). As indicated in section 2, wind blades are designed to survive under 70m/s wind conditions [S4] for conventional turbines. Thus, the increase in the rotation speed does not pose a threat to the wind blade of the proposed HWT, and the blade cost stays unchanged.

As indicated in the mass variation section, to satisfy the increased shaft torque and the shear stress, the low-speed shaft mass needs to be increased by 69.91% (See Table S1). Thus, the cost of the low-speed shaft is increased by 69.91%, as illustrated in Table S3.

The replacement cost of the CVT transmission for a 200 horsepower Nissan engine is $4000-$7000 [S18, S19], which is equivalent to $26.67-46.67/kW. Thus, while applying a 3.33MW VDM on a 2.5MW HWT, the cost of CVT is around $88,000-$154,000, which leads to an increase of 30.66%~53.59% cost as indicated in Table S3.

A Typical VDM in automobile A/C system of modern, which uses around 4 horsepower (3 kW) of the engine's power, costs $180-$220 [S20, S21]. Thus, the cost of VDM is estimated here at $60/kW-$73/kW, which leads to $198,000-$240,000 for a 3.33MW VDM, then the increased cost of the addition of VDM is 92.09%~111.63%.

TES and ASU are the mechanical energy storage units for the proposed HWT. One portion of the collected 1kWh kinetic energy is stored in the TES in the form of air-compression heat, and another portion is collected in the ASU as air-potential energy. The cost of the packed-bed TES storage with concrete utilized for the proposed HWT is $1.46/kWh [S22], and the cost of the underground storage chamber is $2/kWh [S23]. Assuming that the kinetic energy is equally distributed as air-compression heat and air-potential energy, the averaged TES and ASU cost for the storage units is $2.23/kWh. For a 2.5MW HWT with 12h storage capacity and 75% VDM efficiency, the storage costs $88,308. It should be noted that, for the current settings, the storage capacities of TES and ASU are oversized. The ASU and TES costs can be decreased with an optimal sizing approach for potential sites targeted for the installation of the proposed HWTs.

In summary, compared to a conventional WT with the same power capacity, the capital cost of the proposed HWT is increased by 11.49%~15.19%.

Table S3. Capital cost break-down of the 2.5 MW HWT and 2.5 MW WT.

Component	WT	Hybrid WT (Optimistic)		Hybrid WT (Pessmistic)	
	Cost (K$)	Costs (K$)	Increment	Costs (K$)	Increment
Rotor	**932**	**932**		**932**	
Blades	644	644		644	
Hub	121	121		121	
Pitch mchnsm & bearings	156	156		156	
Spinner, Nose Cone	11	11		11	
Drive train,nacelle	**1327**	**1621**		**1730**	
Low speed shaft	10	17	**69.91%**	17	**69.91%**
Bearings	65	65		65	
Gearbox/ **(Gearbox+CVT)**	290	379	**30.66%**	445	**53.59%**
Mech brake, HS cpling etc	8	8		8	
Generator/**(Generator+VDM)**	215	413	**92.09%**	455	**111.63%**
Variable spd eletronics	311	311		311	
Yaw drive & bearing	89	89		89	
Main frame	83	83		83	
Electrical connections	157	157		157	
Hydraulic, Cooling system	47	47		47	
Nacelle cover	52	52		52	
Control, Safety System, Monitoring	**55**	**55**		**55**	
Tower	**658**	**728**	10.59%	**762**	15.86%
Storage (TES+ASU)	**0**	**88**		**88**	
Balance of Station Cost	**1052**	**1064**		**1070**	
Foundations	110	122	10.59%	127	15.86%
Transportation	234	234		234	
Roads, Civil Work	184	184		184	
Assembly & Installation	135	135		135	
Electrical Interface/Connections	300	300		300	
Engineering & Permits	90	90		90	
Initial Capital Cost	**4025**	**4488**	11.49%	**4637**	15.19%

S10. *Parameter settings for the turbine design and operational simulations*

In this section, we depict the parameter settings for the turbine design and operational simulations, including the electricity generation maximization model (23), optimal scheduling model to maximize the revenue in wholesale markets (24), and the unit commit model in Section S8.

We choose 1.5MW wind turbines to investigate the benefits of HWT in China, and 2.5MW wind turbines to investigate the benefits of HWT in the U.S. The parameters of 1.5 MW conventional WT are adopted from GoldWind as indicated in Table S4(A). The parameters of 2.5 MW conventional WT are adopted from General Electric as indicated in Table S4(B).

For the HWT, the charging efficiency and discharging efficiency are set as 80% based on the high-efficiency character of the VDM over broader wind conditions and power conditions, as analyzed in section 4. The rated capacity of VDM is chosen to provide rated electric power even when no wind is available. Thus, the rated power capacity of VDM is 2MW and 3.33MW for the 1.5MW HWT and 2.5MW HWT, respectively. The rated energy capacity of the air tank is 12h for rated VDM capacity, as indicated in Table S4.

Table S4. Parameter settings for the 1.5MW and 2.5 MW HWT and WT.

(A) 1.5MW GoldWind WT and 1.5MW HWT

Parameter	Value	Unit	Parameter	Value	Unit
cut-in speed	3.0	m/s	P_{rated}^{VDM}	2	MW
rated speed	11.0	m/s	$E_{\max}^{str}$	12 P_{rated}^{VDM}	MWh
cut-out speed	22.0	m/s	$E_{\min}^{str}$	$0.1E_{\max}^{str}$	MWh
R^{WT}	38.5	m	η^{Vc}	0.80	——
P_{rated}^{WT}	1.5	MW	η^{Vd}	0.80	——
$\boldsymbol{H}$	**1.8**	**m**	$\boldsymbol{S}$	**0.12**	$\mathbf{m^2}$
$\mathbf{R^D}$	**1.0**	**m**	$\boldsymbol{n^{cy}}$	**23**	——

(B) 2.5MW General Electric WT and 2.5MW HWT

Parameter	Value	Unit	Parameter	Value	Unit
cut-in speed	3.0	m/s	P_{rated}^{VDM}	3.33	MW

rated-speed	12.0	m/s	$E_{\max}^{str}$	$12P_{rated}^{VDM}$	MWh
cut-out speed	25	m/s	$E_{\min}^{str}$	$0.1E_{\max}^{str}$	MWh
R^{WT}	50	m	η^{Vc}	0.80	——
P_{rated}^{WT}	2.5	MW	η^{Vd}	0.80	——
$\boldsymbol{H}$	**2.0**	**m**	$\boldsymbol{S}$	**0.16**	**m²**
R^D	**1.2**	**m**	$\boldsymbol{n^{cy}}$	**23**	——

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