Cost Optimization of Wind Turbine Components

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Abstract: ***The increasing demand for renewable energy sources has driven significant advancements in wind turbine technology. However, the high costs associated with wind turbine components remain a critical challenge. This study explores various strategies for optimizing the cost of wind turbine components. Key areas of focus include material selection, manufacturing processes, and supply chain management. By leveraging advanced materials and innovative manufacturing techniques, such as additive manufacturing and automation, significant cost reductions can be achieved. Additionally, optimizing the supply chain through strategic sourcing and inventory management can further enhance cost efficiency. The integration of predictive maintenance and real-time monitoring systems also plays a crucial role in minimizing downtime and extending the lifespan of wind energy more economically viable but also contributes to the broader goal of sustainable energy development. The findings of this study provide valuable insights for manufacturers, policymakers, and stakeholders in the renewable energy sector, paving the way for more cost-effective and sustainable wind energy solutions.***

Keywords: Renewable energy, Rotor blades, Nacelle, Gearbox, Tower, Control systems, Monitoring equipment, Material selection, Supply chain management, Predictive maintenance, Real-time monitoring, Cost efficiency, Sustainable energy, lifting equipment, Transporting equipment

1. Introduction

Wind energy has become a cornerstone in the global pursuit of sustainable and renewable energy solutions. As the world grapples with the challenges of climate change and the depletion of fossil fuels, wind turbines offer a promising alternative for clean energy generation. Wind turbines are complex systems composed of several critical components, each playing a vital role in the overall efficiency and functionality of the turbine. These components include rotor blades, nacelle, tower, foundation, and ancillary systems such as control and monitoring equipment 0

The rotor blades are perhaps the most visible and crucial components of a wind turbine. They are responsible for capturing the kinetic energy of the wind and converting it into mechanical energy. The design and material selection for rotor blades are critical, as they must withstand varying wind conditions while maintaining structural integrity and efficiency. Advanced materials such as carbon fiber composites are increasingly being used to enhance performance and reduce weight, thereby lowering manufacturing and transportation costs [2]

The nacelle, which sits atop the tower, houses essential components such as the gearbox, generator, and control systems. The gearbox converts the low-speed rotational energy from the rotor blades into high-speed rotational energy suitable for electricity generation. Innovations in gearbox design and materials can significantly impact the overall cost and reliability of the wind turbine. Similarly, the generator, which converts mechanical energy into electrical energy, is a key area for cost optimization. Advances in generator technology, including the use of permanent magnet generators, can improve efficiency and reduce maintenance costs [3]

The tower is another critical component, providing the necessary height to capture optimal wind speeds. The height and material of the tower are crucial factors in determining the overall cost and performance of the wind turbine. Steel is the most used material for towers due to its strength and durability[4]. However, alternative materials such as concrete and hybrid designs are being explored to reduce costs and improve transportation logistics [5]

The foundation of a wind turbine ensures the stability and structural integrity of the entire system. Depending on the location and soil conditions, different types of foundations such as monopile, gravity-based, and floating foundations are used. The choice of foundation has a significant impact on the overall cost and feasibility of wind turbine installation. Innovations in foundation design and construction techniques can lead to substantial cost savings [6]

In addition to these primary components, ancillary systems such as control and monitoring equipment play a crucial role in the efficient operation of wind turbines. Advanced control systems optimize the performance of the turbine by adjusting the blade pitch and yaw to maximize energy capture. Furthermore, lifting and transporting equipment are essential for the installation and maintenance of wind turbines, impacting both cost and logistical efficiency [7] Real-time monitoring systems provide valuable data on the health and performance of the turbine, enabling predictive maintenance and reducing downtime.[8]

Despite the technological advancements, the high costs associated with wind turbine components remain a significant challenge. This study aims to explore various strategies for optimizing the costs of these components [9] By focusing on material selection, innovative manufacturing processes, and efficient supply chain management, substantial cost reductions can be achieved. This comprehensive approach not only makes wind energy more economically viable but also supports the broader goal of sustainable energy development.[10]

2. Blades

2.1 Satellite Workshop

Establishing satellite temporary workshops near wind turbine installation sites for manufacturing blades can significantly reduce transportation costs and logistical challenges[11]. Wind turbine blades are large and cumbersome, making their transportation from manufacturing facilities to installation sites both expensive and complex. By setting up temporary workshops close to the installation locations, the need for long-distance transport is minimized, which can lead to substantial cost savings[12]

These satellite workshops can be equipped with the necessary machinery and tools to manufacture blades on-site. This proximity allows for more efficient use of resources and reduces the risk of damage during transit, ensuring that the blades arrive in optimal condition. Additionally, on-site manufacturing can streamline the supply chain, ensuring timely availability of components and reducing lead times. This approach also allows for quicker response times to any issues that may arise during installation, enhancing overall efficiency and reducing downtime.

The flexibility of temporary workshops means they can be set up and dismantled as needed, providing a cost-effective solution that can be adapted to various project scales and locations. This adaptability is particularly beneficial for wind farms located in remote or hard-to-reach areas, where traditional transportation methods may be impractical or prohibitively expensive [13].

Moreover, local production can support the local economy by creating jobs and utilizing local materials and services. This not only contributes to cost savings but also fosters community engagement and support for renewable energy projects[14]. The environmental impact of transporting large components over long distances is also reduced, contributing to the overall sustainability of the project

However, setting up these workshops does come with challenges, such as the need for infrastructure, skilled labor, and regulatory compliance. Addressing these challenges requires strategic planning and investment. Despite these hurdles, the benefits of reduced transportation costs and logistical challenges make satellite temporary workshops a viable and practical solution for optimizing wind turbine blade manufacturing.[15]

Figure 1
https://www.farmersjournal.ie/what-are-the-options-for-building-a-shed-204155

2.2 Split Blades

Transporting wind turbine blades poses significant logistical challenges due to their length and weight. To address these issues, splitting the blades into smaller sections for transportation can be an effective solution. By dividing the blades into modular segments, they can be transported using standard-sized trucks or rail cars, reducing the need for specialized equipment and permits. This approach simplifies the logistics of navigating narrow roads, bridges, and other infrastructure constraints, making the transportation process more manageable and cost-effective [16].

Once the blade segments arrive at the installation site, they can be reassembled using advanced joining techniques that ensure structural integrity and performance. This method not only lowers transportation costs but also minimizes the risk of damage during transit [17]. Additionally, modular blade design allows for easier handling and storage, further enhancing logistical efficiency.

Implementing this strategy requires careful planning and coordination to ensure that the reassembly process maintains the blades aerodynamic properties and overall performance[18]. The use of precision engineering and high-quality materials in the joining process is crucial to avoid any compromise in the blade's functionality. Advanced techniques such as bolted or bonded joints, along with thorough testing and quality control measures, can ensure that the reassembled blades perform as effectively as their one-piece counterparts.[19]

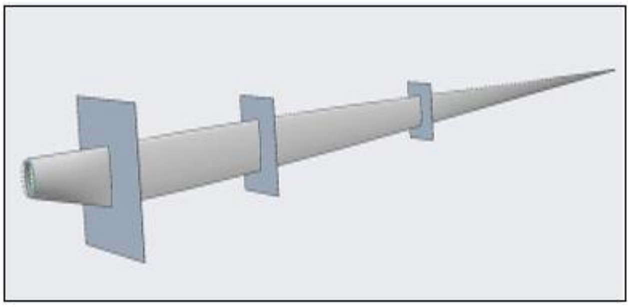

Figure 2

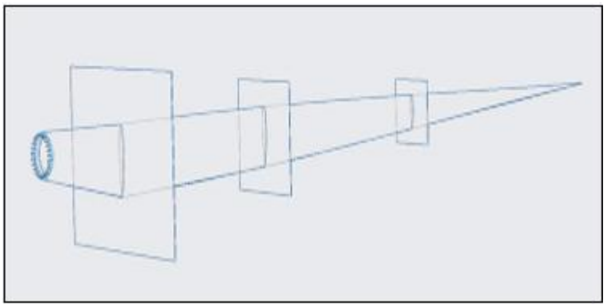

Figure 3

Moreover, splitting the blades can facilitate more flexible and scalable manufacturing processes. Temporary satellite workshops can be established near installation sites to produce and assemble the blade segments, further reducing transportation costs and logistical complexities. This localized production approach supports the local economy by creating jobs and utilizing local materials and services, while also fostering community engagement and support for renewable energy projects.[20]

However, this approach does come with challenges, such as ensuring the precision and durability of the joints, managing the logistics of transporting multiple segments, and maintaining consistent quality control throughout the process[21]. Addressing these challenges requires strategic planning, investment in technology, and collaboration with industry experts. By reducing transportation costs and logistical hurdles, this strategy can contribute to the broader goal of making wind energy more accessible and sustainable.

2.3 Split Blade Mold

Transporting wind turbine blade molds to satellite temporary workshops near installation sites can be challenging due to their size and weight. To address this, splitting the molds vertically into segments can be an effective solution. This approach allows mold to be transported using standard-sized trucks or rail cars, reducing the need for specialized equipment and permits [22]. Here's a detailed explanation of how this can be implemented, along with technical details of the molds.

Wind turbine blade molds are typically made from high-strength materials such as steel or composite materials to withstand the manufacturing process[23]. The molds are designed to precisely shape the blades, ensuring aerodynamic efficiency and structural integrity. They are usually large, single-piece structures that can be up to 100 meters in length for modern wind turbines. This size makes transportation difficult and costly [24].

To facilitate easier transportation, the molds can be split vertically into smaller segments. This involves dividing the mold along its length into sections that can be more easily handled and transported. Each segment must be designed to fit together seamlessly to maintain the precise shape and dimensions required for the blade manufacturing process [25].

Once the segmented molds arrive at the satellite workshop, they need to be reassembled. This requires advanced joining techniques to ensure that the segments align perfectly and maintain the structural integrity of the mold. Using high-strength bolts to secure the segments together. This method allows for easy assembly and disassembly but requires precise alignment to avoid gaps or misalignment. Ensuring precise alignment of the mold segments is crucial. Misalignment can lead to defects in the blades, affecting their performance and safety. To achieve this, alignment pins and guides can be used during the assembly process. These tools help position the segments accurately before they are joined [26].

Maintaining high standards of quality control is essential when using segmented molds. Each segment must be inspected for defects before assembly, and the assembled mold must be tested to ensure it meets all specifications [27]. Non-destructive testing methods, such as ultrasonic or radiographic inspection, can be used to check for internal defects [28].

Smaller segments are easier and cheaper to transport, reducing overall logistics costs. Segmented molds can be transported to various locations, allowing for on-site manufacturing at multiple wind farm sites. Smaller segments are less likely to be damaged during transport, ensuring the mold arrives in optimal condition[29]. Setting up satellite workshops supports local economies by creating jobs and utilizing local services. Reassembling the mold requires precision and expertise. Initial Investment: Designing and manufacturing segmented molds can be costly and Ensuring compliance with local regulations and standards can be challenging [30].

In conclusion, splitting wind turbine blade molds into vertical segments for transportation to satellite temporary workshops offers a practical and economical solution to logistical challenges. By addressing transportation difficulties and reducing costs, this approach supports the efficient and cost-effective production of wind turbine blades, contributing to the broader goal of sustainable energy development.[31]

3. Tower

3.1 Satellite Workshop

Establishing satellite temporary workshops near wind turbine installation sites for manufacturing the tower can significantly reduce transportation costs and logistical challenges. Wind turbine towers are large and heavy structures, often requiring specialized transportation methods that are both expensive and complex[32]. By setting up temporary workshops close to the installation locations, the need for long-distance transport is minimized, leading to substantial cost savings.

Wind turbine towers are typically made from tubular steel or bolted steel shell structures. They can vary in height, commonly ranging from 80 to 140 meters, depending on the specific turbine model and site requirements. The towers are designed to support the nacelle and rotor blades, withstand environmental loads, and ensure the stability of the entire wind turbine system[33].

These satellite workshops can be equipped with the necessary machinery and tools to manufacture tower sections on-site. This proximity allows for more efficient use of resources and reduces the risk of damage during transit, ensuring that the tower sections arrive in optimal condition. Additionally, on-site manufacturing can streamline the supply chain, ensuring timely availability of components and reducing lead times[34]. This approach also allows for quicker response times to any issues that may arise during installation, enhancing overall efficiency and reducing downtime. The flexibility of temporary workshops means they can be set up and dismantled as needed, providing a cost-effective solution that can be adapted to various project scales and locations. This adaptability is particularly beneficial for wind farms located in remote or hard-to-reach areas, where traditional transportation methods may be impractical or prohibitively expensive. Moreover, local production can support the local economy by creating jobs and utilizing local materials and services. This not only contributes to cost savings but also fosters community engagement and support for renewable energy projects.

The environmental impact of transporting large components over long distances is also reduced, contributing to the overall sustainability of the project. However, setting up these workshops does come with challenges, such as the need for infrastructure, skilled labor, and regulatory compliance. Addressing these challenges requires strategic planning and investment. Despite these hurdles, the benefits of reduced transportation costs and logistical challenges make satellite temporary workshops a viable and practical solution for optimizing wind turbine tower manufacturing[35].

Figure 4

3.2 Wooden Towers

Wooden wind turbine towers are being developed using engineered wood, such as laminated veneer lumber (LVL). This material is not only strong and lightweight but also has a much lower carbon footprint compared to steel For instance, using wood can reduce the CO2 emissions in creating a tower by up to 90% Additionally, wooden towers can be easier to transport and assemble on-site, as they can be built in smaller modules This modular construction also reduces the need for heavy machinery and extensive infrastructure during installation

Environmental Benefits are rich in wooden towers which significantly lowers CO2 emissions compared to steel and concrete towers[36]. For example, using engineered wood can reduce emissions by up to 90%. Wood is a renewable resource, and using it helps in carbon sequestration, as trees absorb CO2 during their growth

These towers are made from laminated veneer lumber (LVL), which is created by bonding thin layers of wood together. This process results in a material that is stronger than traditional timber and can even surpass steel in strength-to-weight ratio. Wooden towers are designed to last for decades, with some models having a projected lifespan of 35 years[37]. Wooden towers can be built in smaller, modular sections, making them easier to transport and assemble on-site. This reduces the need for heavy machinery and extensive infrastructure. The modular design allows for the construction of taller towers, which can support larger turbines and generate more energy.

Modvion's Innovations: A Swedish company, Modvion, has been at the forefront of developing wooden wind turbine towers. They recently unveiled a tower designed for the largest onshore turbines, capable of supporting a 6.4 MW turbine, this design has received third-party approval and meets international quality standards. Modvion's towers can reach heights of up to 219 meters, making them suitable for powerful wind turbines. While wood is generally more flammable than steel, engineered wood used in these towers is treated to enhance its fire resistance. Initial costs can be higher due to the need for specialized manufacturing processes, but the long-term benefits and reduced transportation costs can offset this.

Figure 5

3.3 Splitting the Segments of Tower

Splitting wind turbine towers into smaller segments, such as four pieces, offers several practical advantages, particularly in terms of transportation and assembly. This modular approach is gaining traction in the wind energy industry due to its numerous benefits. Compact Stacking method in which smaller segments can be stacked more efficiently, optimizing space during transportation. This is especially beneficial for transporting towers to remote or difficult-to-access locations. Efficient stacking reduces the number of trips required, thereby lowering transportation costs and emissions [38]. Smaller segments can be transported using standard-sized shipping containers or trucks, which simplifies logistics. This flexibility allows for the use of existing transportation infrastructure, avoiding the need for specialized vehicles.

The segments are designed with precise engineering to ensure they fit together seamlessly. This involves advanced joining techniques such as bolting, welding, or adhesive bonding. Accurate joining is crucial for maintaining the structural integrity of the tower, ensuring it can withstand the stresses and loads it will encounter during operation. Segmented towers can be assembled on-site with greater precision[39]. Each piece is designed to fit together accurately, ensuring structural integrity. Modular construction allows for adjustments and modifications to be made more easily during the assembly process

Companies like Modvion are already implementing these techniques with their wooden wind turbine towers. Their modular design allows for efficient transportation and assembly, making the entire process more sustainable and cost-effective. Research on hybrid wind turbine towers, which combine different materials and modular segments, highlights the benefits of this approach in terms of both structural performance and logistical efficiency [40]. Segmenting wind turbine towers into smaller pieces is a smart approach that enhances both the logistical and environmental aspects of wind energy projects. It simplifies transportation, reduces costs, and ensures accurate assembly, contributing to the overall efficiency and sustainability of wind energy solutions.

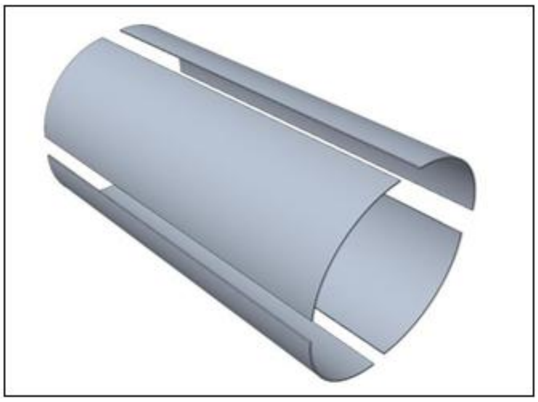

Figure 6

Figure 7

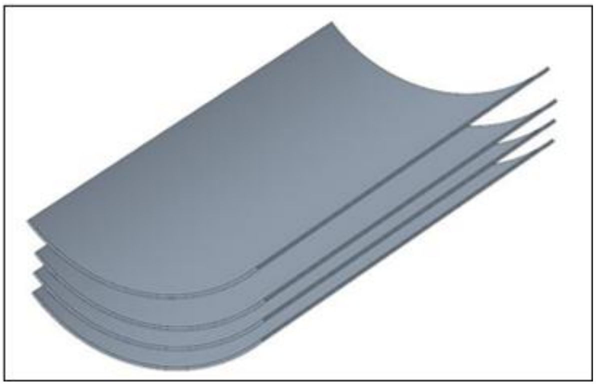

Figure 8

4. Nacelle

Developing modular nacelle designs allows for easier assembly and scalability, which can reduce manufacturing and installation costs and improving the aerodynamic design of the nacelle can reduce drag and increase efficiency and Streamlined Aerodynamics which enhances the aerodynamic design can improve efficiency and reduce the amount of material needed and leading to cost savings in energy production

Utilizing high-strength, lightweight composite materials can significantly reduce the weight of the nacelle, leading to lower material and transportation costs and incorporating nanomaterials can enhance the mechanical properties of components, improving durability and reducing maintenance costs. Incorporating recycled materials can reduce raw material costs and improve sustainability[41]

Using 3D printing technology for producing complex nacelle components can reduce waste and lower production costs and implementing automation and robotics in the manufacturing process can increase precision, reduce labor costs, and enhance production speed. Incorporating energy storage solutions within the nacelle can help manage energy output more effectively, reducing overall operational costs and enhancing the integration with smart grids can optimize energy distribution and reduce downtime[42]. Developing superconducting generators can reduce the size and weight of the nacelle, leading to significant cost savings and using medium-frequency transformers can reduce the weight and volume of the nacelle, making it more compact and cost-effective[43]

Refurbishing aged nacelles by replacing worn-out components and upgrading technology can extend their operational life by 15-20 years. This approach not only reduces waste but also lowers the cost of new installations. The materials used in nacelles, such as metals and composites, can be recycled. Metals can be melted down and reused, while composites can be processed into new materials. This reduces the environmental impact and lowers the cost of raw materials. Decommissioned nacelles can be repurposed for various applications[44]. For example, they can be converted into tiny homes, educational tools, or research facilities. This creative reuse of materials can provide additional value and reduce waste. By leveraging these advanced and innovative approaches, the cost of wind turbine nacelles can be significantly reduced, making wind energy more competitive and sustainable.

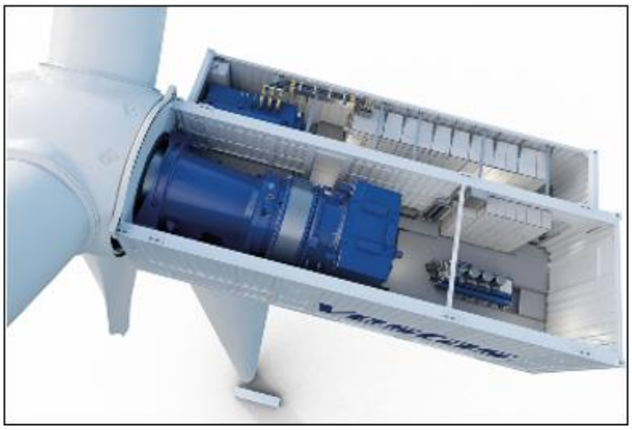

Figure 5

5. Lifting Tools

To ensure the safe and efficient handling of various wind turbine components, different lifting yokes are typically used to accommodate component shape and size, weight distribution, safety requirements, and operational efficiency. However, implementing a single lifting yoke for multiple wind turbine components is a challenging but potentially feasible idea.

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Developing a yoke design that can be adjusted to different shapes, sizes, and weights might involve modular components or adjustable arms configured for specific tasks. It is crucial to ensure that the yoke meets all safety standards and regulations for each type of component it will handle. Design a lifting yoke with interchangeable modules that can be swapped out depending on the component being lifted[45]. This allows for customization without the need for multiple yokes. Creating prototypes and conducting extensive testing with various wind turbine components will help identify any design flaws and ensure the yoke can handle different loads and conditions.

Customizing a lifting yoke to handle different capacity loads within a single yoke is a practical and efficient solution. A customizable lifting yoke can be designed with adjustable components, such as extendable arms or interchangeable attachments, to accommodate various load capacities. This flexibility allows the same yoke to be used for different weights and sizes of loads.

Incorporating hydraulic systems can enable smooth and precise adjustments to the yoke's dimensions and load-bearing capacity. This ensures that the yoke can be quickly adapted to different lifting requirements without compromising safety. A modular design allows for the addition or removal of components based on the specific lifting needs. This can include adjustable beams, spreader bars, and other attachments that can be configured to handle different types of loads.

Custom lifting yokes can be equipped with safety features such as load indicators, locking mechanisms, and overload protection systems. These features help ensure that the yoke operates safely under varying load conditions. Using high-quality materials and robust construction techniques ensures that the lifting yoke can withstand the stresses of lifting different capacities. This durability is crucial for maintaining safety and efficiency in lifting operations.

Custom lifting yokes can be designed to meet all relevant safety and regulatory standards, ensuring that they are suitable for use in various industries and applications. Performing a detailed cost-benefit analysis is essential to ensure that the development and implementation of a versatile yoke are economically viable. Consider factors such as manufacturing costs, potential savings, and long-term benefits.

Figure 6

6. Transportation Tool

Steel bed frames are essential for the transportation of wind turbine components due to their inherent strength and durability. These frames provide a stable base for heavy components such as nacelles, tower sections, and rotor blades, ensuring that these parts are securely held in place during transit and minimizing the risk of damage[4]. Designed to facilitate the easy lifting and handling of large and heavy components, steel bed frames often come equipped with attachment points for cranes and other lifting equipment

Furthermore, steel bed frames can be customized to fit the specific dimensions and shapes of various wind turbine components. This customization optimizes space utilization and ensures the safe transportation of each component. The use of high-quality steel guarantees that the frames can withstand the stresses of transportation, including vibrations, shocks, and varying weather conditions. Each wind turbine component, including nacelles, tower sections, and rotor blades, possesses unique dimensions and shapes[46]. It is recommended that steel bed frames be designed to match these specific requirements, ensuring a snug and secure fit. This customization is crucial in preventing movement and potential damage during transit. These points must be tailored to the weight distribution and balance of each component, facilitating safe and efficient loading and unloading. Custom frames must be designed to meet all relevant transportation regulations and standards. This includes considerations for road, rail, or sea transport, ensuring that the components are moved legally and safely. Furthermore, additional protective features, such as padding or coatings, should be incorporated into the frames to further safeguard the components from damage due to friction or impact during transit.

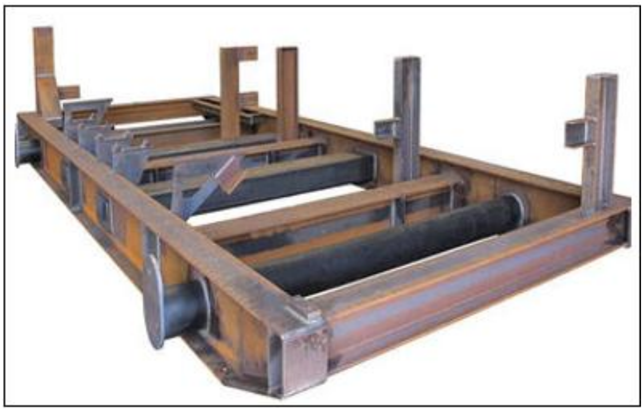

Figure 7

Using hydraulics to expand the horizontal beams of a steel bed frame for customization is an innovative and practical solution for vast utility.

Hydraulic systems allow for precise adjustments to the length and width of the frame, accommodating various sizes of wind turbine components. This flexibility ensures a snug fit for different parts, enhancing stability during transport. Hydraulic mechanisms can be operated with minimal effort, making it easy to adjust the frame dimensions quickly. This feature is particularly useful in dynamic environments where different components need to be transported frequently.

The use of hydraulics ensures that adjustments are smooth and controlled, reducing the risk of sudden movements that could damage the components or cause injury to operators. High-quality hydraulic systems are designed to withstand heavy loads and harsh conditions, ensuring that the frame remains reliable over time. This durability is crucial for the safe transport of heavy wind turbine components.

Using a single, customizable steel bed frame can indeed be a cost-effective solution and by investing in a versatile, adjustable frame, we can reduce the need for multiple specialized frames, thereby lowering overall costs. We can achieve significant cost savings while maintaining the safety and efficiency of transporting wind turbine components.

References

[1] Ghorbani, Y., Zhang, S. E., Nwaila, G. T., Bourdeau, J. E., & Rose, D. H. (2023). Embracing a diverse approach to a globally inclusive green energy transition: Moving beyond decarbonisation and recognising realistic carbon reduction strategies. Journal of Cleaner Production, 434, 140414. https://doi.org/10.1016/j.jclepro.2023.140414

[2] R. Nijssen, G.D. de Winkel,5 - Developments in materials for offshore wind turbine blades, Editor(s): Chong Ng, Li Ran, Offshore Wind Farms, Woodhead Publishing,2016,Pages 85-104,ISBN 9780081007792. https://doi.org/10.1016/B978-0-08-100779-2.00005-2

[3] Muhammad Omer Siddiqui, Paul Robert Feja, Philipp Borowski, Hans Kyling, Amir R. Nejad, Jan Wenske, Wind turbine nacelle testing: State-of-the-art and development trends, Renewable and Sustainable Energy Reviews, Volume 188,2023,113767,ISSN 1364-0321, https://doi.org/10.1016/j.rser.2023.113767

[4] Edwin Hernandez-Estrada, Orlando Lastres-Danguillecourt, Jose B. Robles-Ocampo, Andres Lopez-Lopez, Perla Y. Sevilla-Camacho, Bianca Y. Perez-Sariñana, Jose R. Dorrego-Portela, Considerations for the structural analysis and design of wind turbine towers: A review, Renewable and Sustainable Energy Reviews, Volume 137,2021,110447,ISSN 1364-0321, https://doi.org/10.1016/j.rser.2020.110447.

[5] Jonny Nilimaa, Smart materials and technologies for sustainable concrete construction, Developments in the Built Environment, Volume 15,2023,100177, ISSN 2666-1659, https://doi.org/10.1016/j.dibe.2023.100177

[6] Xiaoni Wu, Yu Hu, Ye Li, Jian Yang, Lei Duan, Tongguang Wang, Thomas Adcock, Zhiyu Jiang, Zhen Gao, Zhiliang Lin, Alistair Borthwick, Shijun Liao, Foundations of offshore wind turbines: A review, Renewable and Sustainable Energy Reviews, Volume 104, 2019, Pages 379-393, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2019.01.012.

[7] Mohd Javaid, Abid Haleem, Ravi Pratap Singh, Shanay Rab, Rajiv Suman, Significance of sensors for industry 4.0: Roles, capabilities, and applications, Sensors International, Volume 2,2021,100110, ISSN 2666-3511, https://doi.org/10.1016/j.sintl.2021.100110

[8] Larbi Brahimi, Nadji Hadroug, Abdelhamid Iratni, Ahmed Hafaifa, Ilhami Colak, Advancing predictive maintenance for gas turbines: An intelligent monitoring approach with ANFIS, LSTM, and reliability analysis, Computers & Industrial Engineering, Volume 191,2024,110094,ISSN 0360-8352, https://doi.org/10.1016/j.cie.2024.110094.

[9] Sukanta Roga, Shawli Bardhan, Yogesh Kumar, Sudhir K. Dubey, Recent technology and challenges of wind energy generation: A review, Sustainable Energy Technologies and Assessments, Volume 52, Part C,2022,102239, ISSN 2213-1388ISBN 9780128181157, https://doi.org/10.1016/j.seta.2022.102239.

[10] E. Manavalan, M. Thanigai Arasu, Jayakrishna Kandasamy, Chapter 14 -Sustainable supply chain management in manufacturing industries, Editor(s): Kapil Gupta, Konstantinos Salonitis, In Handbooks in Advanced Manufacturing, Sustainable Manufacturing, Elsevier, 2021, Pages 343-365, ISBN 9780128181157, https://doi.org/10.1016/B978-0-12-818115-7.00010-9.

[11] Sunghun Hong, Jade McMorland, Houxiang Zhang, Maurizio Collu, Karl Henning Halse, Floating offshore wind farm installation, challenges and opportunities: A comprehensive survey, Ocean Engineering, Volume 304,2024, 117793, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2024.117793.

[12] Bhaba R. Sarker, Tasnim Ibn Faiz, Minimizing transportation and installation costs for turbines in offshore wind farms, Renewable Energy, Volume 101, 2017, Pages 667-679, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2016.09.014

[13] Daniela Ritter-Hayashi, Joris Knoben, Patrick A.M. Vermeulen, Success belongs to the flexible firm: How labor flexibility can retain firm innovativeness in times of downsizing, Long Range Planning, Volume 53,

Issue 3, 2020, 101914, ISSN 0024-6301, https://doi.org/10.1016/j.lrp.2019.101914.

[14] Sara Toniolo, Chiara Pieretto, Daniela Camana, Improving sustainability in communities: Linking the local scale to the concept of sustainable development, Environmental Impact Assessment Review, Volume 101, 2023, 107126, ISSN 0195-9255, https://doi.org/10.1016/j.eiar.2023.107126.

[15] Weiwei Zhang, Hao Yu, Binbin Yin, Arslan Akbar, K.M. Liew, Sustainable transformation of end-of-life wind turbine blades: Advancing clean energy solutions in civil engineering through recycling and upcycling, Journal of Cleaner Production, Volume 426, 2023,139184, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2023.139184.

[16] Yogesh K. Dwivedi, Anand Jeyaraj, Laurie Hughes, Gareth H. Davies, Manju Ahuja, Mousa Ahmed Albashrawi, Adil S. Al-Busaidi, Salah Al-Sharhan, Khalid Ibrahim Al-Sulaiti, Levent Altinay, Shem Amalaya, Sunil Archak, María Teresa Ballestar, Shonil A. Bhagwat, Anandhi Bharadwaj, Amit Bhushan, Indranil Bose, Pawan Budhwar, Deborah Bunker, Alexandru Capatina, Lemuria Carter, Ioanna Constantiou, Crispin Coombs, Tom Crick, Csaba Csáki, Yves Darnige, Rahul Dé, Rick Delbridge, Rameshwar Dubey, Robin Gauld, Ravi Kumar Gutti, Marié Hattingh, Arve Haug, Leeya Hendricks, Airo Hino, Cathy H.C. Hsu, Netta Iivari, Marijn Janssen, Ikram Jebabli, Paul Jones, Iris Junglas, Abhishek Kaushik, Deepak Khazanchi, Mitsuru Kodama, Sascha Kraus, Vikram Kumar, Christian Maier, Tegwen Malik, Machdel Matthee, Ian P. McCarthy, Marco Meier, Bhimaraya Metri, Adrian Micu, Angela-Eliza Micu, Santosh K. Misra, Anubhav Mishra, Tonja Molin-Juustila, Leif Oppermann, Nicholas O'Regan, Abhipsa Pal, Neeraj Pandey, Ilias O. Pappas, Andrew Parker, Kavita Pathak, Daniel Pienta, Ariana Polyviou, Ramakrishnan Raman, Samuel Ribeiro-Navarrete, Paavo Ritala, Michael Rosemann, Suprateek Sarker, Pallavi Saxena, Daniel Schlagwein, Hergen Schultze, Chitra Sharma, Sujeet Kumar Sharma, Antonis Simintiras, Vinay Kumar Singh, Hanlie Smuts, John Soldatos, Manoj Kumar Tiwari, Jason Bennett Thatcher, Cristina Vanberghen, Ákos Varga, Polyxeni Vassilakopoulou, Viswanath Venkatesh, Giampaolo Viglia, Tim Vorley, Michael Wade, Paul Walton, "Real impact": Challenges and opportunities in bridging the gap between research and practice – Making a difference in industry, policy, and society, International Journal of Information Management, Volume 78, 2024, 102750, ISSN 0268-4012, https://doi.org/10.1016/j.ijinfomgt.2023.102750.

[17] Lumír Pečený, Pavol Meško, Rudolf Kampf, Jozef Gašparík, Optimisation in Transport and Logistic Processes, Transportation Research Procedia, Volume 44, 2020, Pages 15-22, ISSN 2352-1465, https://doi.org/10.1016/j.trpro.2020.02.003.

[18] Tawse, Alex & Tabesh, Pooya. (2021). Strategy implementation: A review and an introductory framework. European Management Journal. 39. 22-33. https://doi.org/10.1016/J.EMJ.2020.09.005.

[19] S. Razzaq, Z.X. Pan, H.J. Li, S.P. Ringer, X.Z. Liao, Joining dissimilar metals by additive manufacturing: A review, Journal of Materials Research and Technology, Volume 31, 2024, Pages 2820-2845, ISSN 2238-7854, https://doi.org/10.1016/J.JMRT.2024.07.033.

[20] He Yu, Tao Wang, Yuancheng Dong, Qiuqin Gou, Lei Lei, Yunqi Liu, Numerical investigation of splitter blades on the performance of a forward curved impeller used in a pump as turbine, Ocean Engineering, Volume 281, 2023, 114721, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2023.114721.

[21] Liat Haber, Abraham Carmeli, Leading the challenges of implementing new technologies in organizations, Technology in Society, Volume 74, 2023, 102300, ISSN 0160-791X, https://doi.org/10.1016/j.techsoc.2023.102300.

[22] Zhiyu Jiang, Installation of offshore wind turbines: A technical review, Renewable and Sustainable Energy Reviews, Volume 139, 2021, 110576, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2020.110576.

[23] Sri Sai P. Reddy, Rohan. Suresh, Hanamantraygouda. M.B., B.P. Shivakumar, Use of composite materials and hybrid composites in wind turbine blades, Materials Today: Proceedings, Volume 46, Part 7, 2021, Pages 2827-2830, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.02.745.

[24] Guo Guangxing, Zhu Weijun, Sun Zhenye, Fu Shifeng, Shen Wenzhong, Yang Hua, Large wind turbine blade design with mould sharing concept based on deep neural networks, Sustainable Energy Technologies and Assessments, Volume 73, 2025, 104131, ISSN 2213-1388, https://doi.org/10.1016/j.seta.2024.104131.

[25] Ken Mills, Chapter 1.9 - How Mold Fluxes Work, Editor(s): Seshadri Seetharaman, Treatise on Process Metallurgy, Elsevier, 2014, Pages 435-475, ISBN 9780080969886, https://doi.org/10.1016/B978-0-08-096988-6.00006-7.

[26] Assembly and dismantling, Editor(s): R L TIMINGS, Basic Engineering Technology, Butterworth-Heinemann, 1988, Pages 175-195, ISBN 9780434919499, https://doi.org/10.1016/B978-0-434-91949-9.50014-9.

[27] Lev M. Klyatis, Eugene L. Klyatis, CHAPTER 4 - PRACTICAL ACCELERATED QUALITY DEVELOPMENT AND INPROVEMENT IN MANUFACTURING AND DESIGN, Editor(s): Lev M. Klyatis, Eugene L. Klyatis, Accelerated Quality and Reliability Solutions, Elsevier Science, 2006, Pages 363-411, ISBN 9780080449241. https://doi.org/10.1016/B978-008044924-1/50005-8.

[28] Sandeep Kumar Dwivedi, Manish Vishwakarma, Prof. Akhilesh Soni, Advances and Researches on Non Destructive Testing: A Review, Materials Today: Proceedings, Volume 5, Issue 2, Part 1, 2018, Pages 3690-3698, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2017.11.620.

[29] Marcel Turkensteen, Gerard Sierksma, Jaap E. Wieringa, Balancing the fit and logistics costs of market segmentations, European Journal of Operational Research, Volume 213, Issue 1, 2011, Pages 340-348, ISSN 0377-2217, https://doi.org/10.1016/j.ejor.2011.02.027.

[30] Ian Merrell, Jeremy Phillipson, Matthew Gorton, Paul Cowie, Enterprise hubs as a mechanism for local

economic development in rural areas, Journal of Rural Studies, Volume 93, 2022, Pages 81-91, ISSN 0743-0167, https://doi.org/10.1016/j.jrurstud.2022.05.016.

[31] Jelle Joustra, Bas Flipsen, Ruud Balkenende, Structural reuse of wind turbine blades through segmentation, Composites Part C: Open Access, Volume 5, 2021, 100137, ISSN 2666-6820, https://doi.org/10.1016/j.jcomc.2021.100137.

[32] M. Asgarpour, 17 - Assembly, transportation, installation and commissioning of offshore wind farms, Editor(s): Chong Ng, Li Ran, Offshore Wind Farms, Woodhead Publishing, 2016, Pages 527-541, ISBN 9780081007792, https://doi.org/10.1016/B978-0-08-100779-2.00017-9.

[33] C. Rebelo, A. Moura, H. Gervásio, M. Veljkovic, L. Simões da Silva,Comparative life cycle assessment of tubular wind towers and foundations – Part 1: Structural design, Engineering Structures, Volume 74,2014, Pages 283-291, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2014.02.040.

[34] M. Eugeni, T. Quercia, M. Bernabei, A. Boschetto, F. Costantino, L. Lampani, A. Marchetti Spaccamela, A. Lombardo, M. Mecella, L. Querzoni, R. Usinger, M. Aliprandi, A. Stancu, M.M. Ivagnes, G. Morabito, A. Simoni, A. Brandão, P. Gaudenzi, An industry 4.0 approach to large scale production of satellite constellations. The case study of composite sandwich panel manufacturing, Acta Astronautica,Volume 192, 2022, Pages 276-290, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2021.12.039.

[35] Xianbo Zhao, Yongjian Ke, Jian Zuo, Wei Xiong, Peng Wu, Evaluation of sustainable transport research in 2000–2019, Journal of Cleaner Production, Volume 256, 2020, 120404, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.120404.

[36] Austin Himes, Gwen Busby, Wood buildings as a climate solution, Developments in the Built Environment, Volume 4, 2020, 100030, ISSN 2666-1659, https://doi.org/10.1016/j.dibe.2020.100030.

[37] B. Castanié, A. Peignon, C. Marc, F. Eyma, A. Cantarel, J. Serra, R. Curti, H. Hadiji, L. Denaud, S. Girardon, B. Marcon, Wood and plywood as eco-materials for sustainable mobility: A review, Composite Structures, Volume 329, 2024, 117790, ISSN 0263-8223, https://doi.org/10.1016/j.compstruct.2023.117790.

[38] Jelle Joustra, Bas Flipsen, Ruud Balkenende, Structural reuse of wind turbine blades through segmentation, Composites Part C: Open Access, Volume 5, 2021, 100137, ISSN 2666-6820, https://doi.org/10.1016/j.jcomc.2021.100137.

[39] F. Delzendehrooy, A. Akhavan-Safar, A.Q. Barbosa, R. Beygi, D. Cardoso, R.J.C. Carbas, E.A.S. Marques, L.F.M. da Silva, A comprehensive review on structural joining techniques in the marine industry, Composite Structures, Volume 289, 2022, 115490, ISSN 0263-8223, https://doi.org/10.1016/j.compstruct.2022.115490.

[40] L.M. Martulli, M. Diani, G. Sabetta, S. Bontumasi, M. Colledani, A. Bernasconi, Critical review of current wind turbine blades' design and materials and their influence on the end-of-life management of wind turbines, Engineering Structures, Volume 327, 2025, 119625, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2025.119625.

[41] Wen Zhang, Jun Xu, Advanced lightweight materials for Automobiles: A review, Materials & Design, Volume 221, 2022, 110994, ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2022.110994.

[42] Vilas J Kharat, Puran Singh, G Sharath Raju, Dinesh Kumar Yadav, M Satyanarayana.Gupta, Vanya Arun, Ali Hussein Majeed, Navdeep Singh, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, Materials Today: Proceedings, 2023, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.11.033.

[43] A.B. Abrahamsen, N. Magnusson, B.B. Jensen, M. Runde, Large Superconducting Wind Turbine Generators, Energy Procedia, Volume 24, 2012, Pages 60-67, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2012.06.087.

[44] Kumar Kanishka, Bappa Acherjee, A systematic review of additive manufacturing-based remanufacturing techniques for component repair and restoration, Journal of Manufacturing Processes, Volume 89, 2023, Pages 220-283, ISSN 1526-6125, https://doi.org/10.1016/j.jmapro.2023.01.034.

[45] Thanikasalam, Kumaran. (2024). Design and Kinematic Analysis of a Two-Sided Asymmetric Scotch Yoke Mechanism with Variable Stroke Length https://doi.org/10.31224/4096

[46] Md Hosne Mobarak, Md. Aminul Islam, Nayem Hossain, Md. Zobair Al Mahmud, Md. Thohid Rayhan, Nushrat Jahan Nishi, Mohammad Asaduzzaman Chowdhury, Recent advances of additive manufacturing in implant fabrication – A review, Applied Surface Science Advances, Volume 18, 2023, 100462, ISSN 2666-5239, https://doi.org/10.1016/j.apsadv.2023.100462.

[47] Francesco Sciatti, Paolo Tamburrano, Elia Distaso, Riccardo Amirante, Digital hydraulic valves: Advancements in research, Heliyon, Volume 10, Issue 5, 2024, e27264, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2024.e27264.