Due to the extraordinary physical characteristics of utility scale wind turbine generator components, packaging plays an outsized role in cargo protection and transportation. Expanding global markets, extended supply chains, and larger turbine designs are convergent factors prompting a rethink in reverse logistics management and packaging design. This paper examines the implications of packaging and reverse logistics in the wind energy industry and explores packaging innovations and reverse logistics best practices. We start by providing an overview of wind turbine generator equipment and types of packaging, followed by information on packaging life cycle and asset management, and close with discussions on supply chains, reverse logistics management and packaging innovation. Logistics practitioners and supply chain managers will be mainly interested in the contents of this paper and may benefit from the strategies and tactics described herein.
Overview
The rise of wind energy as a viable source of renewable energy has significantly increased demands on the transportation industry. With rotor heads in excess of 80 metric tons and blades longer than 50 meters, utility scale wind turbine generator (WTG) equipment is arguably one of the most challenging types of cargo to transport. Due to its unique size and shape, WTG equipment requires an extraordinary approach to packaging. While the primary purpose of packaging is to protect cargo during handling and transport, WTG packaging also has a significant impact on supply chain costs.

As depicted in Figure 1, developing regions represent the largest potential for growth in wind energy capacity. As emerging markets are penetrated, packaging will need to play a more prominent role as shippers contend with extended supply chains and transportation infrastructure issues.

Figure 1: Global Wind Energy Capacity Growth 2007 vs. 2020 Moderate Scenario

The main purpose of this paper is to examine how WTG packaging design and reverse logistics affect supply chain management and explore ways shippers can leverage packaging as a competitive advantage.

WTG Equipment
For the purpose of this paper we will focus on packaging requirements for utility scale, horizontal axis wind turbine cargo. The major WTG components vary by manufacturer and model, but generally consist of a tower, nacelle, and rotor. Each of these components has its own unique physical characteristics as described below.

The Tower is the structural support component of the wind turbine, and is typically tubular steel. Towers are commonly 60 to 100 meters in height, and are transported lengthwise in three to five separate sections. The base section is the most challenging to transport. It has the greatest diameter among the sections (width and height dimension for transport). Towers are lifted with belly straps (slings) or by means of wire rope with hooks that connect to the flange.

The Nacelle (a/k/a turbine) rests on top of the tower and houses the main shaft, gearbox, and generator. It is the most valuable of the main components and can weigh in excess of 80 metric tons. Nacelles are normally lifted from the top by means of specialized lifting gear. Access to the lifting points is typically gained through hatch covers (portals). Some nacelles are modular by design. These modular units individually weigh less than a complete nacelle, but they must be transported separately to the wind farm resulting in an increased number of shipments.
The **Rotor** consists of a hub and blades which is attached to the nacelle. The blades catch the wind to turn the rotor. There are normally three blades per rotor; each blade is “balanced” and matched in a “set”. Rotor diameter commonly ranges from 80 to 100 meters with single blade length up to 50 meters. Blades are usually composed of a fiberglass composite which makes them extremely susceptible to damage during transport.

**WTG Packaging**

Depending on the industry and application, packaging can have several fundamental purposes such as protecting and preserving products, facilitating product handling and transport, aggregating products for storage, informing product composition, and marketing products to customers. Packaging design is normally thought of in the context of consumer goods and distribution. Consumer packaging is typically made of plastic and paper materials with a premium put on its ability to market itself to consumers. Distribution packaging is used for bulk handling, warehousing, and transport with the most common form being the palletized unit load.

WTG components require packaging that is substantially different from these common forms. Most components must be individually packaged due to their size, weight and shape. A typical WTG packaging system consists of a steel frame, lifting and securing points, and tarpaulins. The system supports and protects the component during transport and storage, facilitates handling and shields against environmental exposure. Some packaging systems also include padding (bumpers) that acts as a buffer between the steel frame and the machined surface of the component.

Estimates of transportation costs in the wind industry vary, but are generally considered to be in the range of 10 – 15% of overall investment\[^2\]. This percentage is significantly higher than other industries, with transportation costs representing about 3% of cost of goods sold\[^3\]. There is significant potential for cost reduction by implementing best in class transport strategies. For instance by utilizing rail instead of truck over long distances, transport costs can be reduced by 50 percent\[^4\]. The purpose of this section is to examine packaging as it affects transportability and therefore transportation costs.

We can condense functional attributes of WTG packaging into four main categories that impact costs. The first category to consider is **Multi use**. Is the packaging designed for single use and disposal or multiple uses? If reusable, then we need to estimate the number of expected reuses and consider the costs to maintain and return these assets (i.e. reverse logistics). The second category is **Stackability**. Stackable packaging enables us to more efficiently use space by loading in tiers (e.g. cargo stacked on the deck of a vessel), therefore reducing storage and transport costs. However, stackable packaging requires a stronger more expensive frame. The third category relates to **Modality**. Multi modal packaging is designed for more than one transport mode (i.e. vessel to rail to truck) and seeks to minimize handling costs incurred from transferring components between modes. The final category is **Universality**, which relates to the ability of the packaging to accommodate more than one type of product within the same family (e.g. 34m and 41m blades).

Each of these categories can affect supply chain costs and complexity as outlined in Table 1. While cost implications typically drive decision making, it is also important to consider complexity. Additional complexity can lead to hidden costs, particularly if a system grows so complicated that it becomes unmanageable. Synergies may be found by combining multiple attributes that result in a more sophisticated design. For instance a stackable packaging design might also incorporate multi use functionality, because design and procurement costs are already relatively high. A sophisticated design is likely to be more robust and flexible in its application, but will have higher costs per package. A simpler less flexible design will be cheaper and easier to manage, but will provide fewer strategic advantages.
Table 1: Packaging effects on Supply Chain Costs and Complexity

<table>
<thead>
<tr>
<th></th>
<th>Cost:</th>
<th>Single Use</th>
<th>Multi Use</th>
<th>Non Stackable</th>
<th>Single Mode</th>
<th>Multi Modal</th>
<th>Dedicated Use</th>
<th>Universal Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design &amp; Procurement</td>
<td>Complexity:</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Cargo</td>
<td>Complexity:</td>
<td>x</td>
<td>x</td>
<td>↑</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Transport</td>
<td>Complexity:</td>
<td>x</td>
<td>x</td>
<td>↑</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Cargo Handling</td>
<td>Complexity:</td>
<td>x</td>
<td>x</td>
<td>↑</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Storage</td>
<td>Complexity:</td>
<td>x</td>
<td>x</td>
<td>↑</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Reverse Logistics</td>
<td>Complexity:</td>
<td>x</td>
<td>x</td>
<td>↑</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Sustainability</td>
<td>Complexity:</td>
<td>↑</td>
<td>↓</td>
<td>x</td>
<td>x</td>
<td>↑</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

In order to produce an effective WTG packaging design, it is important to engage a cross functional team consisting of internal and external stakeholders that can evaluate supply chain requirements. Product engineering can advise component carrying/handling requirements and the maximum force that components can withstand during transportation. Outside parties such as naval architects and trailer manufacturers can provide information on the forces and elements that components will be exposed to during transportation. Information derived from commercial operations and direct materials sourcing can provide insight into the supply chain. Logistics, in coordination with transportation service providers, can provide guidance on travel limitations, transportation infrastructure concerns and specialized equipment constraints. Field personnel can explain conditions for storing and maneuvering components at the wind farm site.

By engaging supply chain stakeholders up front, it is possible to get a better initial understanding of the total cost of ownership for different packaging options. Establishing a supply chain based concept for packaging before the design process begins can help to avoid design omissions that may contribute to costly redesigns later in the product development process.

As product life cycles decrease, improving time-to-market is becoming a strategic priority for industry leaders. The WTG packaging design process should be incorporated into new product introduction efforts to ensure safe and cost effective transportation of the new component. Ideally, the packaging design process utilizes quality control methods such as QFD (quality function deployment) in order to transform supply chain stakeholder requirements into engineering priorities. There are several WTG packaging design elements that can help improve total cost of ownership. Part standardization helps reduce procurement and maintenance costs. Consideration should be made for

![Figure 2: Packaging Stowed in a 40' Container](image)
whether the design calls for materials in metric or imperial units and if it is backwards compatible with existing designs. Reducing the total number of parts simplifies the reverse logistics process, limits the number of replacement parts that must be stocked, and simplifies end of life tasks such as recycling and disposal. Poka-yoke design principles can help prevent end user errors. Parts should be properly labeled and manuals clearly written. Suppliers must be able to easily set up the packaging then load the component for shipment. Project site personnel must be able to safely unload components and break down the packaging for return shipping. Use of color coding and symbols can be effective, particularly if supply chain partners have different native languages. Ideally, packaging set up/brake down should be possible using standard tools and require a limited number of actions. The method for asset tracking (e.g. serialization) should be carefully considered to properly manage inventory, correlate manufacturing defects to suppliers, and satisfy customs requirements that may be part of the reverse logistics process (e.g. temporary import to avoid duty and tax). Finally, it is important to consider reverse logistics requirements. Packaging design should take into consideration the method of return transportation - truck, rail, ocean, or air and the cost benefits of utilizing standard transport equipment such as sea containers. See Figure 2 for an example of packaging stowed in a 40’ ocean container.

Life Cycle Management
Organizations are increasingly reviewing environmental impacts from operations. Many government programs specifically focus on reducing waste from packaging (e.g. Directive 94/62/EC). In 1990, Thomas Lindqvist coined the term Extended Producer Responsibility (EPR) for the policy of promoting total life-cycle environmental improvements of product systems by extending the manufacturer’s responsibilities to various parts of the product’s life cycle. In the wind energy industry, manufacturers typically maintain ownership of packaging after use (i.e. it is not sold as part of the product). By actively managing the “post use” portion of the packaging life cycle, manufacturers can reduce their environmental impact and realize financial benefits.

The current strategies for sustainable material use are the classics: reduce, reuse, recycle on a massive industrial scale. In order to prioritize these activities, it is beneficial to consider The Waste Hierarchy (see Figure 3) in the overall WTG packaging design. For example, ensuring that a package is not over-engineered can lead to decreased material requirements and reduced freight costs due to lower shipment weight. Some parts may be destroyed during the disassembly process; for example steel wires that are cut when the component is unloaded. A reusable alternative such as Kevlar ratchet straps should be considered.

Figure 3: The Waste Hierarchy

Asset Management
Manufacturers may account for reusable packaging as plant and equipment to be depreciated or as inventory to be expensed. Regardless, standard principles of asset management should be used to optimize a fleet of reusable packaging. The fleet size and corresponding investment must be carefully balanced with the high cost of stock outs, because WTG components cannot be shipped without packaging. Making volume purchases is beneficial to keep unit costs low.

In order to calculate the ideal fleet size, critical factors such as supply/demand, WTG component production plans, outbound transportation cycles - supplier(s) to wind farm(s), reverse logistics cycles - wind farm(s) to supplier(s), and packaging production lead time must be considered. Other factors include demand seasonality, component production ramp up, and project delays (i.e.
unanticipated requirements for component storage. It is also important to understand when the packaging is required in the component production process. For example nacelle packaging is usually required at the beginning of the process, whereas blade packaging is usually needed at the end of the process.

Inventory turns is a common business performance metric that compares the ratio of costs of goods sold to average inventory. A modified inventory turnover calculation is suggested for packaging. Costs of goods sold could be replaced with number of WTG units shipped and average inventory could be replaced with average packaging inventory. By comparing this measure over time, we may infer whether or not the packaging fleet size is being actively managed to improve "turns". The data may need to be normalized, in cases where the supply chain has changed over time, to account for changes in outbound and reverse logistics cycles (i.e. an increase in foreign sourced components may drive up cycles which would require more packaging to be deployed all other factors being equal).

Supply Chain
In order to leverage packaging as a competitive advantage, WTG shippers will need to have some insight into future supply chain requirements. Penetrating new markets will require an analysis of transportation infrastructure and regulations. A basic analysis of transportation size and weight restrictions can identify issues such as escort requirements and travel restrictions. Designing a package that eliminates or reduces the need for trip escorts can reduce freight costs and simplify transportation scheduling activities. New markets may also have special cargo securement guidelines. Anticipating these requirements in advance may eliminate the need for costly redesign.

It is also important to evaluate the types and availability of transportation and cargo handling equipment, particularly in emerging and frontier markets. An interesting example is Brazil, where recent auctions have resulted in significant growth opportunities for wind turbine installations over the next several years. Many shippers are now evaluating transportation infrastructure and equipment in Brazil in order to determine how to deliver existing WTG models to project sites. It is clear that the combination of significant growth with underdeveloped infrastructure will provide many challenges to shippers. Shippers that find ways to adapt to the Brazilian market as opposed to trying to adapt Brazil to their current model will achieve competitive advantages.

Offshoring production to LCC's (low cost countries) is a noted supply chain trend. However, factors such as rising fuel costs and potential appreciation of the Yuan have prompted discussion about near sourcing. The wind energy industry is a likely candidate for near sourcing due to high transportation costs, which in some cases are reported to be 20% – 25% of the total WTG cost. While it can be difficult to predict the trend of the entire industry over the next several years, it is important for shippers to understand what their particular strategy will be over the short to medium term.

For example, take a shipper that is currently sourcing 100% of its blades for wind farms located in the Midwest United States from India. It may be beneficial for this shipper to design a stackable multi modal package. Its blades could then be loaded several tiers high during the ocean voyage and easily transferred from truck to vessel to rail. However, what if there is a plan to shift 50 – 75% of production to a local supplier allowing blades to be transported via truck only? The shipper's packaging may be significantly over engineered for truck transport and its ROI will be disappointing. Had the firm had insight into this development they could have engaged strategies to reduce the required fleet size of their stackable fixtures (i.e. transload from stackable to non-stackable at the US port of import) or developed adaptable packaging that could be used for transport from both suppliers (i.e. non-stackable packages with stackable attachments).

Reverse Logistics Management
Reverse logistics can be broadly defined as the process of moving goods from their typical final destination for the purpose of capturing value or proper disposal. In the wind energy industry
reverse logistics activities are focused on damaged or obsolete WTG components and packaging. For the purposes of this paper, we will focus on the challenges associated with packaging: many-to-one distribution channels, insufficient quality assurance, poorly defined return processes, disparate IT systems, and budgetary conflicts. In order to overcome these challenges shippers must avoid a reactionary system and form a strategic reverse logistics management program.

Over time WTG equipment suppliers will likely deliver components to more than one wind farm site, therefore reverse logistics must cope with many-to-one (see Figure 4) or many-to-many distribution channels. Reverse logistics begins at the wind farm site with field personnel whose primary focus is to install and commission turbines. Reverse logistics is a secondary consideration, which can make it difficult to implement packaging return processes.

Inadequate processes and controls can lead to return shipments with missing parts, unreported damaged parts, mismatched parts from different packaging types, and loads that are not fully optimized. For international returns, missing parts etc. can negatively impact customs compliance, particularly if packaging is imported under a temporary import or export regime.

Figure 4: International WTG Packaging – Simplified Supply Chain Map

Ultimately the WTG equipment manufacturing facility will receive the return packaging shipment and sort out parts, refurbish packaging, and redistribute parts that may have been incorrectly shipped. These activities are not core competencies of the manufacturer, who may not have the expertise or manpower to adequately perform these non-value added tasks. Marshalling the packaging through a third party distribution operation which handles inspection and repair activities can be an effective alternative. Benefits to this approach may include:

1. Reduced spare parts inventory from centralizing stock keeping units at one location
2. Improved accounting accuracy and consistency from dedicated receiving, inspection, cross-dock, put away, pick, and ship processes
3. Extended reusable packaging life cycles from utilizing an operation with specialized handling, refurbishment (metal working), and distribution capabilities
4. Increased fulfillment flexibility from consolidating the packaging inventory versus delivering all packaging directly back to the WTG equipment manufacturers
5. Greater economies of scale from a third party distribution operation
In Figure 3, the distribution operation is located closest to the WTG equipment manufacturer, but it could be positioned closer to the wind farm site(s) depending on supply chain configuration. Eighty percent of a company's supply chain costs are locked in during the design and planning of the supply chain strategy\textsuperscript{14}. Therefore, it is important to think of the distribution operation in the context of the overall supply chain. Ideally it would be one part of a larger supply chain modeling program such as SCOR (Supply-Chain Operations Reference-model).

In the book "Going Backwards: Reverse Logistics Trends and Practices" the authors estimate that reverse logistics costs account for approximately a half percent of the total U.S. GDP\textsuperscript{15}. It is clear that streamlining reverse logistics processes can become a strategic advantage for companies (or a strategic disadvantage if not properly managed). However, shippers continue to prioritize IT investments on the outbound supply chain (e.g. order management and fulfillment). Consequently, most organizations live with labor intensive, manual, often undisciplined and inefficient returns management processes\textsuperscript{16}.

Gaining visibility into packaging inventory across the extended supply chain and aggregating the information is a necessary first step towards improving reverse logistics performance. Process controls and inventory reporting are standard capabilities included with most Enterprise Resource Planning (ERP) systems. Integrating inventory information for orders of new packaging shipped from packaging suppliers to WTG manufacturers is relatively straightforward. However, it is more difficult to integrate inventory information for deployed packaging shipped from WTG manufacturer to wind farm site, packaging at the site, and packaging being returned to WTG manufacturer.

There are several ways to track deployed packaging inventory. Whether through a Transportation Management System (TMS) or Excel spreadsheets, packaging must be captured as an additional component of the overall system. It is important to use standard data elements with inventory reports to reduce process complexity and time spent aggregating data. Visibility of forward and reverse packaging flows produces a true picture of inventory levels and inventory velocity.

Reverse logistics begins at the wind farm site, or in some cases for foreign sourced WTG components, at the port of import where the packaging is removed before the WTG component is transferred to a different transport mode for on-carriage. It is important to note that wind farm sites are often located in remote areas that lack the resources of a typical shipping facility. Therefore, it is important that processes for handling and preparing packaging for return transport are aligned with available physical and electronic resources. For instance, if field personnel are required to band packaging frames together, palletize and shrink wrap parts, and confirm transportation pick up, methods for procuring materials and communicating remotely must be established.

It is essential that field personnel be trained to identify different types of packaging by means of standard naming conventions. A name that inherently describes the purpose of the packaging and the packaging function (i.e. Tower_100m_Stackable) will improve communication. Methods of packaging identification such as engraved serialization, EAN-13 barcode, RFID/GPS tags, enable inventory tracking and inventory status across the extended supply chain. A packaging reference manual that includes information such as part number, physical description and photo, weight and dimensions, number and type of parts, and handling methods should be distributed among supply chain partners and maintained through document control procedures.

Clear communication can minimize the risk that packaging is shipped to the wrong location or mismatched to part numbers in IT systems. Standard naming conventions and identification methods reduce the complexity of tracking the entire packaging fleet and facilitates reporting and analysis (e.g. days in temporary import, inventory turns, and total cost of ownership by supplier).

Ideally, each individual part of a package is labeled separately. This enables parts to be identified when the package is disassembled. However, attempting to track every single part of each package significantly increases the volume of data that must be managed. The hypothetical example illustrated in Table 2 demonstrates how a ten-fold decrease in data can be achieved by rationalizing tracking units. A further argument for rationalization concerns inventory status.
Typically when an individual part is lost or damaged, the package cannot be used until a replacement part is made available. Therefore, instead of tracking at the individual part level, it is often beneficial to track at the package level and record its associated inventory status.

**Table 2: Tracking Unit Comparison for a 50 turbine project**

<table>
<thead>
<tr>
<th>Turbine Components</th>
<th>Packages per Turbine</th>
<th>Piece per Package</th>
<th>Total Packages</th>
<th>Total Pieces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower Sections:</td>
<td>4</td>
<td>14</td>
<td>200</td>
<td>2800</td>
</tr>
<tr>
<td>Blades:</td>
<td>3</td>
<td>10</td>
<td>150</td>
<td>1500</td>
</tr>
<tr>
<td>Machine head:</td>
<td>1</td>
<td>14</td>
<td>50</td>
<td>700</td>
</tr>
<tr>
<td>Rotor Head:</td>
<td>1</td>
<td>11</td>
<td>50</td>
<td>550</td>
</tr>
<tr>
<td>Control Cabinets:</td>
<td>2</td>
<td>5</td>
<td>100</td>
<td>500</td>
</tr>
</tbody>
</table>

**TRACKING UNITS:** 550 6050

In order to successfully utilize IT in the field, it is essential to avoid unnecessary complexity. Field personnel are likely to be limited in the way they access IT systems due to constraints on time and physical access. Systematic methods for scheduling reverse logistics tasks and for reporting the status of forward and reverse cargo flows, enable field personnel to more effectively monitor transportation schedules, plan equipment and personnel, and confirm pick ups and deliveries.

**Innovation**

There are many opportunities for WTG packaging innovation. Advancements in design can reduce operational costs and total cost of ownership. Implementing systems technology can help optimize cargo flow and aid supply chain planning. Utilizing alternative materials and active end of life cycle management can contribute to improvements in sustainability.

Innovative designs are those that completely rethink the process of how WTG components are handled and transported. Nooteboom’s load floor adapters are an example of an innovation in how nacelles are handled. Typically nacelles are built on a base frame and the entire unit is loaded onto a trailer using an overhead crane. Nooteboom Special Products developed a system that integrates the Vestas nacelle base frame with the trailer, and makes it possible to load/unload 2 MW nacelles without an overhead crane.[17] This system not only reduces handling costs by eliminating the crane and crew, but it also simplifies receiving planning. Trail King’s EFX Extendable Blade Hauler and Schnable Gooseneck Systems for towers[18] are other examples of integrating packaging with transportation equipment and are also "universal" because they can accommodate a variety of products from the same family (e.g. different types of blades). GE’s “Transportation Unit for a Wind Turbine Rotor Blade”[19] is an example of a modular packaging design that increases operational efficiency. This system allows blades to be transported by truck and stacked in tiers during an ocean voyage, with the addition of a specially designed rack. The system facilitates intermodal transport by reducing the risk of handling damage, because blades do not need to be transferred from one package type to another.

There is ample scope for technology innovation. For instance, ERP systems can be extended to include reverse logistics functionality (e.g. SAP Service Parts management)[20] and existing technology can be integrated with IT systems. GPS and RFID tags are existing technologies that can be integrated with technology systems to provide inventory tracking, identification and status information. In a typical deployment, the tags are placed on WTG components and later removed at the wind farm site when the component has been delivered. The tags are then gathered and returned to the WTG manufacturers. However, if the tags are integrated with the packaging instead, they can be used to track both the forward flow of components from WTG manufacturer to wind farm site and the reverse flow of reusable packaging back to the manufacturer. The ability to accumulate tracking data on packaging returns can help improve asset management and identify
bottlenecks in reverse logistics flows. Technology innovation can help shippers optimize reverse logistics flows and ultimately may lead to reduced inventory carrying costs.

There are also ways to increase sustainability through innovation. Use of green materials can reduce the environmental impact of packaging. Enkev’s Cocolok is an example of an alternative to synthetic padding materials, and is made from natural coconut fibers and natural latex.\[^{20}\]

**Conclusion**

Shippers need to understand how developing market dynamics and WTG product life cycles are impacting outbound supply chains, in order to effectively design and procure WTG packaging. Shippers will find that integrating multiple types of packaging solutions can yield overall cost benefits, but this may increase the complexity of supply chain planning and execution activities. In order to fully optimize wind energy supply chains, shippers will need to further develop reverse logistics capabilities, fully leverage systems technology solutions and develop innovative WTG packaging designs.

**References**


