Design Guidelines for Deployable Wind Turbines for Defense and Disaster Response Missions

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Abstract. Access to on-site electrical energy is critical to ensuring a successful military or humanitarian response to conflicts and disasters. These missions typically rely on access to liquid fuel that could be vulnerable to disruption or attack during transport. Generating power on location with wind technology—whether at a contingency base or disaster response coordination point—can reduce this risk and enhance mission reach by diversifying energy sources. Common characteristics of these missions are short planning and execution time horizons and a global scope of potential locations. Compared to conventional wind turbine applications, defense and disaster response applications place a premium on rapid shipping and installation, short-duration operation (days to months), and quick teardown upon mission completion. These design drivers depart from features found in conventional distributed wind turbines, thus necessitating unique design guidance. The supporting information for this guidance comes from available relevant references, technical analyses, and input from industry and military stakeholders. This paper serves as a summary of the full report, *Design Guidelines for Deployable Wind Turbines for Military Operational Energy Applications* (Sandia report SAND2021-14581 R [1]), which presents the best currently available design guidance for deployable wind turbines to facilitate the effective development and acquisition of technology solutions to support mission success.

1. Deployable Wind Applications

This document summarizes guidance on the design and operation of deployable wind systems that provide maximum value to missions in defense and disaster relief. The report, *Market Opportunities for Deployable Wind Systems for Defense and Disaster Response* [2], and a subsequent assessment of currently available commercial wind turbines identified three proposed size ranges for deployable wind systems to address three defense and disaster response applications with unique design requirements. One system is for individual or small teams, whereas the other two are for contingency bases of different scales. The general characteristics of each are as follows:

1.1. *Wind System for Individual, Small Team, or Small Unmanned Station*

- Highly mobile; setup and takedown in minutes
- Lightweight; packable by person or small trailer
- Generally, less than 3 kilowatts (kW) of power
- Primary application is charging batteries and small electronics.

1.2. Wind System for Contingency Base - Small

- Support a portion of the loads of a company-sized element or disaster response team (~300 personnel) with deployments from weeks to months
- Setup and takedown in hours
- Physical dimensions and weight driven by logistics capabilities; common shipping containers
- Generally, single-unit maximum rated power is 10 to 20 kW
- Multiple units deployed and integrated into microgrid with other generation and storage
- Primary application is general AC operational loads.

1.3. Wind System for Contingency Base - Large

- Support a portion of the loads of a battalion or brigade-sized (~1,000–3,000 personnel) element, with deployments from months to more than a year
- Setup and takedown in hours to days
- Physical dimensions and weight driven by logistics capabilities, possibly including specialized equipment
- Generally, single-unit maximum rated power is up to ~100 kW
- Multiple units deployed and integrated into microgrid with other generation and storage
- Primary application is general AC operational loads.

2. Overview of Mobile Electric Power Systems

Mobile energy systems include liquid-fuel generators, photovoltaic (PV) systems, and wind energy systems, with the last currently in early-stage commercialization. Most military contingency operations rely on diesel-powered generators to provide electricity to mission-related loads. As a result, logistics capabilities and requirements, operator training and skills, and typical equipment for operational energy systems are primarily driven by these generators. This is an important consideration for designing a deployable wind system that is compatible not only technically, but logistically, with existing power generation systems.

2.1. Small Expeditionary Power Sources

The E2S2 Product Director Small Expeditionary Power Sources (PD SEPS) provides expeditionary energy solutions that are less than 5 kW. Current products are 2-kW and 3-kW tactical generators, with newer technologies in development to support platoon-scale power needs. There are also early-stage technical products to provide individual-level power below 1 kW.

2.2. Advanced Medium Mobile Power Source

The Advanced Medium Mobile Power Source (AMMPS) line of generators from 5 kW to 60 kW are replacing the prior line of military Tactical Quiet Generators (TQGs), although both are currently in operation. AMMPS generators can be skid-mounted, trailer-mounted, or configured in a microgrid.

2.3. Large Diesel Power Systems

The largest mobile electric power systems start at 100 kW and generally include more advanced distribution systems to power larger bases. The Large Advanced Mobile Power Sources (LAMPS) generators are 100 kW and 200 kW in size. The Deployable Power Generation & Distribution System (DPGDS) is the largest mobile power system at 840 kW as a prime power unit (as compared to smaller tactical power units) to be used as part of a distribution system with transformers and lines to deliver power to loads.

2.4. Existing Deployable Photovoltaic Systems

Unlike wind turbines, there is a large selection of deployable photovoltaic systems with a variety of sizes and configurations designed for a wide array of uses. Some specific examples of adoption by the U.S. Department of Defense (DOD) are listed below:

- The Air Force Research Laboratory tested monocrystalline solar panels on top of tents that were integrated into a trailer-mounted microgrid in 2016 [3]. The project was to test feasibility of integrating a deployable power system into a forward-operating base as part of an initiative to have a totally deployable, self-sustaining power system.

- The Dutch military has deployed thin-film solar systems in Afghanistan, and more recently in Mali [4]. In Mali, their system is a 100% deployable power unit that combines storage, solar, and diesel. Although the system has two 250-kW generators, most of the power comes from the flexible thin-film solar panels.
- The U.S. Army upgraded a surveillance system at the start of 2014, and part of the upgrade was integrating an alternative energy system to improve reliability and increase autonomy when deployed in remote, off-grid locations [5]. The energy system the U.S. Army deployed as part of the upgrade includes 16.8 kilowatt-hours of energy storage, a 2.7-kW solar array, and the capability to automatically start and stop the 5-kW TQG.
- A U.S. Army research team, along with foreign soldiers, tested a human-portable, rucksack-born solar system in 2016 [6]. It was found that the system performed well during the exercise and could reduce the logistical burden of carrying batteries during missions.
- Although not necessarily deployable solar, there are over 400 megawatts of solar generation spread across domestic military bases [7], with future goals of increasing that amount. These prior projects offer an opportunity for lessons learned when deploying solar.

2.5. *Existing Deployable Wind Systems*
Several deployable wind energy concepts and products were explored; three products are shown here as examples. Figure 1 shows the wind + solar + storage system from HCI Energy that is transported via a 20-foot (ft) shipping container. Figure 2 shows the trailer-mounted system from Uprise Energy featuring a telescoping tower and 10-kW wind turbine which fits within a standard 20-ft container for transport. Figure 3 shows the Deployable Advanced Renewable Power System (DARPS) under development by Bergey Windpower which utilizes two, 15-kW Bergey Excel 15 wind turbines on a mobile microgrid structure that transports as a 40-ft container.

Figure 1. HCI Energy

Figure 2. Uprise Energy

Figure 3. Bergey DARPS

3. Mission Planning
The potential benefit of a deployable wind turbine to a particular mission can be assessed during the mission planning stage. The potential power production of a wind turbine requires, at a minimum, two pieces of information: the likely wind resource during the span of the mission and the power curve of the available wind turbine.

3.1. *Wind Resource Information*
Personnel will require access to wind resource data to estimate the power and energy production of the wind turbine in the mission area. The most accurate wind resource data will be specific to a location, at the height of the wind turbine, and specific to the time of day and year of the mission. There are free and paid databases for this information globally, though high-quality validated data are lacking for much of

the world, and the resulting uncertainty in estimated energy production should be anticipated. Some wind resource assessment considerations include:

- For individual/small team systems, referencing an average annual wind speed map nearest to the ground level is likely sufficient, as the performance will likely be strongly influenced by the local topography during the short deployment. The resource will generally be less predictable and more turbulent at this height/scale.
- Bases with shorter missions (less than 1 year) should be aware of potential seasonal variations in wind resource.
- Already established or enduring bases may have or be able to acquire actual wind resource data at the site to improve performance estimates to guide decisions.
- For airborne wind systems, the operational height above ground is typically much higher than even the largest tower-mounted systems. In general, the wind resource increases with height to the top of the atmospheric boundary layer.

3.2. Wind Turbine Power Curve
A deployable wind turbine should be designed to operate in a wide range of wind speeds to maximize global deployment potential. Average global wind speeds at heights nearer to the ground (less than 50 meters [m]) tend to be much lower than those where commercial turbines are operating. It is important to consider very low-wind-speed rotor designs that can extract more energy at lower wind speeds. Wind turbine power curves (power output as a function of wind speed) are part of the standard turbine technical documentation produced through a certification test. The power curve and the average wind speed and distribution are the primary inputs to calculate an expected annual energy production.

3.3. Mission Constraints
It is also important to consider the mission constraints regarding the potential deployment (siting) of a wind turbine. Requirements around electromagnetic, acoustic, and visual signatures, as well as physical obstruction with base operations both on the ground and in the air, may limit the deployment of a wind turbine. Special consideration should be given to airborne wind systems that have very long (over 200 m) tethers that traverse the airspace in often complex patterns. Those impacts may be mitigated through careful design and siting if sufficient specifications are provided during the design stage.

4. Transportation Logistics
The entire process of transportation from manufacturing location to deployment should be considered in the design of a deployable wind turbine. Adhering to standard shipping equipment and regulations will facilitate access to the most applications.

4.1. Container Analysis
An analysis was performed of the maximum size turbine that can be transported in standard 20-ft and 40-ft International Standardization Organization shipping containers. Table 1 lists container dimensions.

Table 1. Standard shipping container dimensions [8]

	Exterior			Interior			Door Opening		Tare Weight
	Length	Width	Height	Length	Width	Height	Width	Height	
20-ft Standard Container	6.1 m (20 ft)	2.4 m (8 ft)	2.6 m (8 ft 6 in)	5.9 m (19 ft 3 in)	2.3 m (7 ft 8 in)	2.4 m (7 ft 9-7/8 in)	2.3 m (7 ft 8 in)	2.3 m (7 ft 5 in)	2,290 kg (5,050 lbs)
40-ft Standard Container	12.2 m (40 ft)	2.4 m (8 ft)	2.6 m (8 ft 6 in)	12.0 m (39 ft 5 in)	2.3 m (7 ft 8 in)	2.4 m (7 ft 9-7/8 in)	2.3 m (7 ft 8 in)	2.3 m (7 ft 5 in)	3,629 kg (8,000 lbs)

4.2. Assumptions of Container Analysis

Turbine system components to be transported in the container include the blades, tower, nacelle, foundation base, inverter, and controls. Although larger turbines may require multiple containers, it is preferred to have a complete system in a single container. A horizontal-axis wind turbine is the assumed archetype.

4.3. Blades

A horizontal-axis wind turbine will typically have three blades. Blade length is important as energy capture is proportional to the square of the rotor radius. For this analysis, the maximum blade length is assumed equal to the interior length of the container. There are three ways to gain extra blade length: blades can be segmented, blades can be placed corner-to-corner in the container, or rotor diameter can be increased using hub extenders. Segmented blades and hypotenuse placement are assumed to be impractical at this time, but the use of hub extenders will be further examined. Hub extenders are occasionally used in the industry to increase rotor diameter, and thus energy capture, without increasing blade length. Based on past and current hub extender use, this analysis assumes a maximum increase in rotor diameter of 14%, which will increase rotor swept area by 30%.

4.4. Maximum Rotor Size

Table 2 shows the maximum rotor radius, rotor diameter, and rotor swept area for the 20-ft and 40-ft containers for both the baseline assumption of no hub extenders (blade length is equal to rotor radius) and with hub extenders (assuming a maximum increase in rotor radius of 14%).

Table 2. Maximum rotor size per container

Container	Max Rotor Radius	Max Rotor Diameter	Max Rotor Swept Area
20 ft (no hub extenders)	5.9 m (19.3 ft)	11.7 m (38.5 ft)	108.2 m^2 (1164.2 ft^2)
20 ft (with hub extenders)	6.7 m (22 ft)	13.4 m (43.9 ft)	140.6 m^2 (1512.9 ft^2)
40 ft (no hub extenders)	12.0 m (39.4 ft)	24.0 m (78.8 ft)	453.5 m^2 (4881 ft^2)
40 ft (with hub extenders)	13.7 m (44.9 ft)	27.4 m (89.9 ft)	589.3 m^2 (6343.4 ft^2)

4.5. Maximum Turbine Power

Figure 4 shows the rotor swept areas and rated power of various small wind turbines currently on the market. The yellow shaded region represents the range of rated power for a given swept area. The general industrywide trend is toward lower specific power with rotor size increasing for a given rated power, thus increasing energy capture at lower wind speeds. For the 20-ft container, the rated power of the maximum rotor size could range from the 11-kW Gaia turbine with its 13-m (42.7-ft) rotor to the 30-kW Bestwatt with a 13.1-m (43 ft) rotor. For the 40-ft container, the rated power of the maximum rotor size could range from about 80 kW to 125 kW, but with fewer models in this range, a maximum rated power of 100 kW is a reasonable assumption.

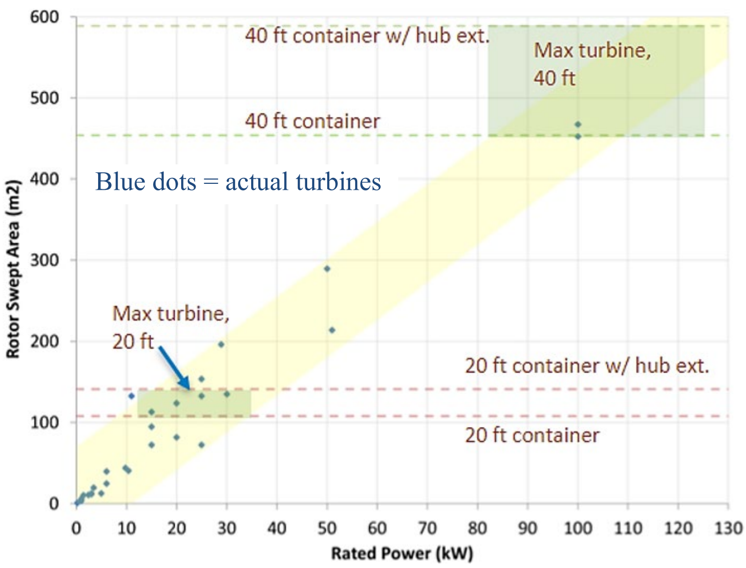

Figure 4. Rated power versus rotor swept area

4.6. Maximum Tower Height

Deployable turbine towers are typically either monopole (no guy wires), guyed towers, or telescoping. They can be a single piece or segmented. This analysis assumes the maximum tower segment length is equal to the interior length of the container. For the 20-ft container, the maximum tower height ranges from 5.9 m (19.3 ft) for one segment to 29.3 m (96.3 ft) for five segments. For the 40-ft container, the maximum tower height ranges from 12.0 m (39.4 ft) for one segment to 36.0 m (118.3 ft) for three segments. Although more segments could fit in the container, a maximum deployable tower height of approximately 30 m (~100 ft) was assumed.

5. Installation

5.1. Siting
Proper siting of the deployable turbine for installation is very important to achieve the best performance and minimize conflicts with the mission and impacts of local topology and obstructions. Mitigating potential conflicts with base activities will be mission-specific but having clear documentation on the wind turbine physical and signature characteristics would help facilitate effective on-site placements.

5.2. Foundation
It is preferred and sometimes required that the deployable turbine foundation cannot significantly disturb the local ground surface. Preferred configurations would be placed on the ground with ballast or deployable outriggers. In some instances, it may be allowable to have a foundation that could be set in a hole and backfilled (no concrete) or based on helical piles that can be screwed in and removed when decommissioned, assuming the equipment to do so was readily available. Simple leveling capabilities should be designed into the system, as should some tolerance for being out of plumb.

5.3. Foundation Analysis
This study considers the stability of nonpermanent foundation options for deployable wind turbines packaged into 20-ft and 40-ft shipping containers as foundations, as well as trailer-mounted systems that fit into a 20-ft shipping container.

5.4. Assumptions of Foundation Analysis
This analysis explores the 1-year and 50-year extreme winds and assumes the turbine has reached cut-out in those extreme winds and the rotor is parked. Overturning moments from extreme winds are modeled per the simplified load methodology in International Electrotechnical Commission (IEC) 61400-2 edition 3. A minimum factor of safety of 1.5 is assumed (i.e., the resistance to the overturning moment should be at least 1.5 times the extreme wind overturning moment).

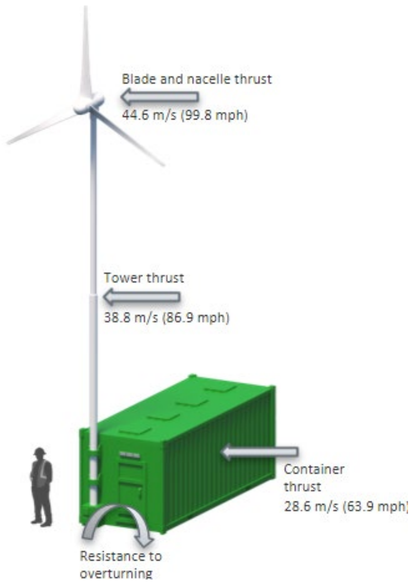

Figure 5. Overturning moments and resistance to overturning

5.5. Modeling
Modeling was performed on the three deployable turbine systems shown in Figures 1, 2, and 3. A generic model was developed to inform foundation guidelines for a range of turbine sizes. Load case H of the simplified loads methodology in the IEC 61400–2 standard, Extreme Wind Loading, was used to calculate thrust loads and overturning moments. As shown in Figure 5, thrust loads on the rotor blades and nacelle result in an overturning moment with a moment arm equal to the turbine hub height. Tower thrust loads assume a moment arm of half the hub height. Thrust loading on the container side is significant, but the assumed moment arm is only half the container height. The system will resist overturning with a counteracting moment of the total system weight times a moment arm of half the container width.

5.6. Maximum Capabilities per Foundation Type
Figure 6 shows the foundation options explored in this analysis. The capabilities of each option are described below. As a general caveat, the commercial wind turbine examples provided below for reference are generally not configured for a deployable operation.

5.6.1. 20-ft container with no outriggers

A 20-ft container with no outriggers was found to serve as a sufficient foundation for a turbine with a rotor diameter up to 5.4 m (17.7 ft), or two turbines with rotor diameters of 3.5 m (11.5 ft). For example, the 3.5-kW Sonsight Wind SS3 has a rotor diameter of 5.0 m (16.4 ft).

5.6.2. 20-ft container with outriggers

For rotor diameters greater than 5.4 m (17.7 ft), outriggers are required to prevent overturning up to a rotor diameter of 11.9 m (39 ft) or up to the maximum turbine that will fit into a 20-ft container. At a maximum 13.4-m (44 ft) rotor diameter (utilizing hub extenders), earth anchors are required on the end of each outrigger. Examples of turbines in the maximum range include the 20-kW QED PHX 20, with a 12.6-m (41.3 ft) rotor diameter, or the 30-kW Bestwatt 30, with a 13.1-m (43 ft) rotor diameter.

5.6.3. 20-ft trailer with outriggers

For trailer-mounted systems that transport in a 20-ft shipping container, the thrust force on the trailer is slightly lower than a container, and with outriggers this system can support a turbine with a rotor diameter up to 12 m (39 ft). For example, the 15-kW EAZ 12 has a 12-m (39.4 ft) rotor diameter.

5.6.4. 40-ft container with outriggers

Larger turbines have longer blades, thus requiring a 40-ft shipping container for transport and foundation. A 40-ft container with outriggers will resist overturning in 44.7-meter-per-second (100 miles per hour) winds for a rotor diameter up to 17.4 m (57 ft) or up to the maximum size that will fit into a 40-ft container, or 27.4-m (90-ft) rotor diameter if earth anchors are added to the outriggers. As an example, the NPS 100 has a range of rotor diameters from 21 m (69 ft) to 27 m (88.6 ft).

5.6.5. Independent, ballasted system

Ballasted foundations, such as offered by ARE Telecom, can also be an option for a deployable wind turbine. Many options exist, and it is recommended that the foundation and tower be engineered for the specified wind turbine and balance of system.

5.6.6. Airborne wind energy

Airborne wind energy was also briefly explored as a potential option for deployable systems. These systems can be packaged and transported in shipping containers, and the container is often used as part of the foundation. Larger airborne systems can use outriggers to prevent overturning during high tether forces. Other systems transport and deploy from a trailer. The foundation structures are designed and engineered for the specific airborne systems and were not further analyzed in this study.

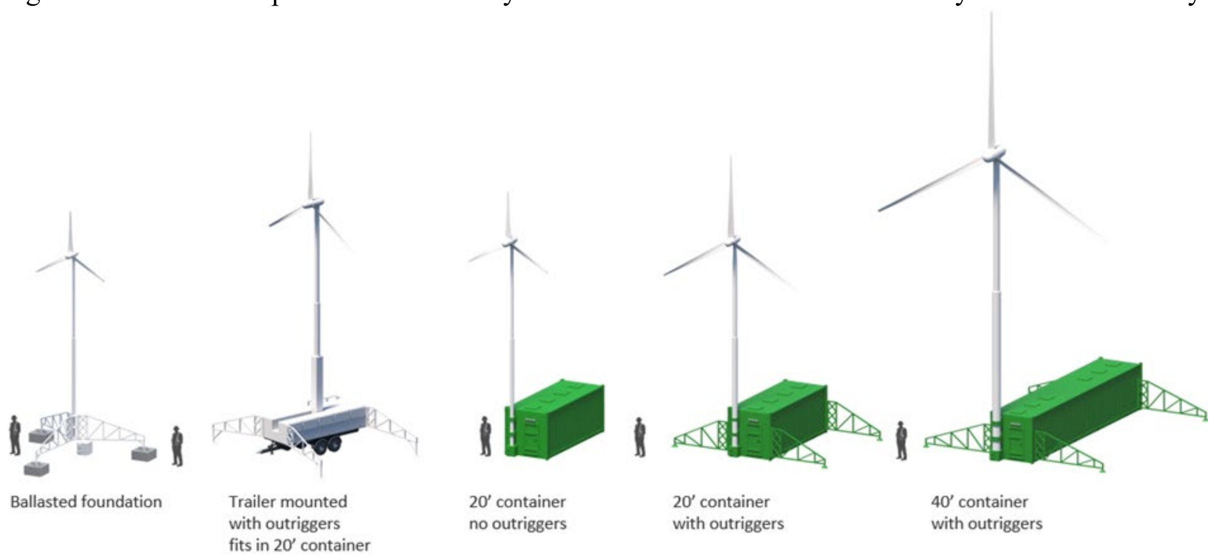

Figure 6. Summary of foundation options explored

5.7. *Overturning Summary*
Figure 7 summarizes the results of the foundation modeling and analysis. As rotor diameter increases, the overturning moment increases. To maintain the minimum 1.5 factor of safety for the resistance to overturning as rotor diameter increases, outriggers are added, followed by earth anchors.

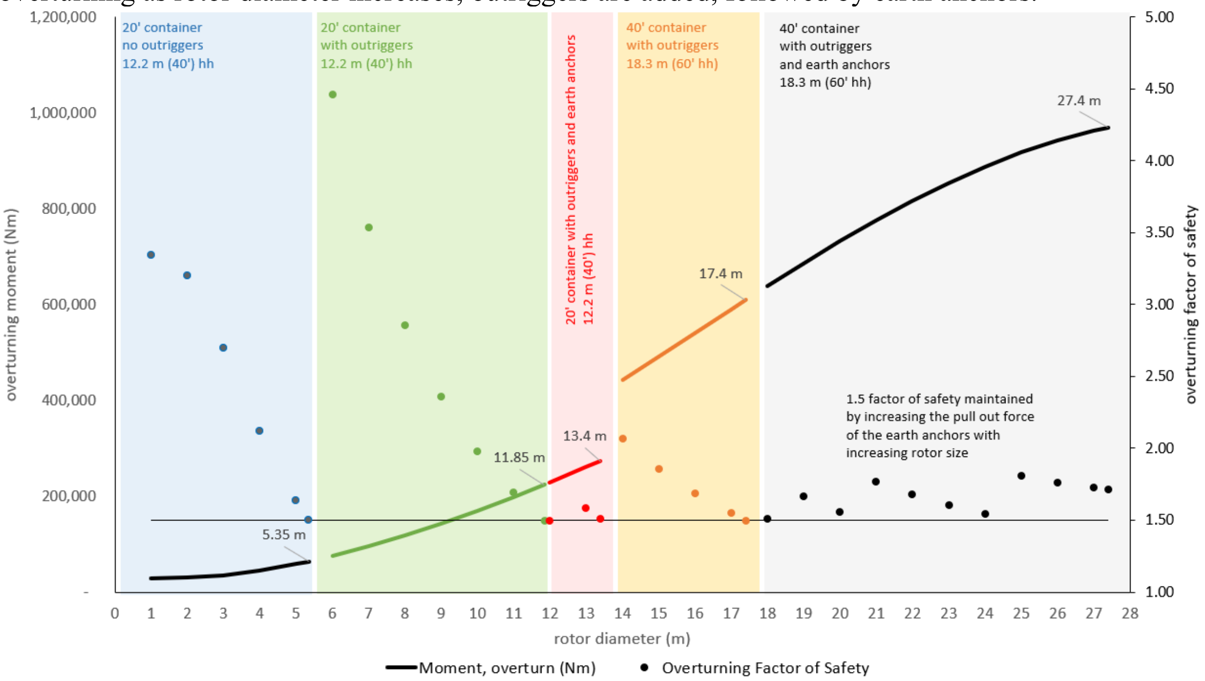

Figure 7. Overturning summary graph

5.8. *Tower*
There is a trade-off between a taller tower for increased energy production and a shorter tower for ease of installation, shipping, reduced visual signature, and airspace conflict. The rotor should be higher than nearby vegetation and structures to avoid a significant reduction in energy production. The design choice between guyed and free-standing towers should consider time and complexity of setup, physical footprint, and obstructions. Structural weight may be a bigger driver than cost or a long design life, especially for the human-portable systems. Lightweight materials, like aluminum and glass or carbon-fiber composites, may be viable design choices. Time to erect and lower is critical for human-portable systems and for storm survival of systems that have rotors optimized for low wind speeds.

Airborne wind generators have some unique benefits, such as not requiring a tower and the ability to reach more consistent and higher wind speeds hundreds of meters off the ground. However, those systems have moving tethers, sometimes carrying electrical power, that are also hundreds of meters long that must be considered as part of the airspace use and potential conflict. In addition, airborne wind turbine technology is still in development and early-stage commercialization.

5.9. *Assembly*
In general, the deployable wind system should be assembled with minimal personnel, training, tools, and time. A small team should ideally be capable of setting up the wind turbine system with the standard equipment without special training beyond what might be required to set up a diesel generator, for example. If nonstandard tools are unavoidable, they should be supplied with the turbine with backups, and if possible be commercial off-the-shelf for ease of replacement. Individual components should not be too heavy or awkward. For the turbine at a larger site, installation support may be provided from a military occupational specialty, such as an interior electrician (12R, 1141) or tactical power generation specialist (91D, 1142), along with more specialized equipment, or a contractor. The training guide for the tactical power generation specialist (91D) is a good reference for the skills and tasks typical for this military occupational specialty [9].

6. Operation and Maintenance

6.1. Operation
The deployable turbine should be as easy and intuitive to operate as mobile diesel generators. Safety systems should be incorporated into the design or operation of the turbines to mitigate the damage of harsh conditions such as extreme winds or icing. It may be beneficial to include special operating modes that support mission requirements, such as reduced acoustic, visual, or electromagnetic signatures.

6.2. Maintenance
The deployable wind turbine should require minimal maintenance while deployed but can likely be inspected more frequently than typical commercial systems. A good basis for reference would be the maintenance requirements for the AMMPS diesel generators. System faults should be easy to diagnose and repair with supplied parts and tools, preferably commercial off-the-shelf tools to facilitate ease of sourcing. It may be more convenient to conduct specialized maintenance between deployments.

7. Power System Integration
Unlike diesel spot generators, a deployable wind turbine will not be directly connected to a load unless the load is a rechargeable battery as in the case of the human-portable system. The deployable wind turbine should be designed to integrate into hybrid power systems to include, at a minimum, a battery storage device, but also likely diesel generators and solar photovoltaics. Those devices could be incorporated as part of an integrated power system or as part of a distributed microgrid with some sort of control system. Currently, DOD has a draft tactical microgrid standard, but it needs further development to account for the nondispatchable nature of wind energy production. A microgrid standard is also lacking on the industry side, though both the IEC and UL (UL3001) are working on microgrid standards. Until a DOD standard is in place, deployable turbines should be designed to meet Institute of Electrical and Electronics Engineers 1547-2018 and IEC and UL microgrid standards. Another important design consideration for hybrid microgrid power systems is the energy management strategy. The choice of using dispatchable diesel power vs. nondispatchable renewable power and battery charge and discharge timing can all have significant impacts on component life, efficiency, and overall fuel savings. This is an active area of research and development broadly.

8. Conclusions
Recommendations are provided for the design and operation of deployable wind systems for defense and disaster relief applications. By considering energy needs and commercially available wind turbines, it was determined that most applications could be broken into one of three configurations: *i)* an individual or small team requiring up to 3 kW for small electronics charging and power, *ii)* teams of up to 300 people where wind could supply 10 kW to 20 kW per shipping container, and *iii)* larger teams where systems up to 100 kW are most appropriate. For the latter two scenarios, standard shipping containers were considered for transport and provide partial or complete structural support for the turbines.

For fast deployment and wide applicability, the 10-kW to 20-kW systems in a 20-ft shipping container have a particularly high potential impact. They can be transported efficiently, for example, to a disaster response command site, assembled in a matter of hours, and in some cases quickly integrated with supplementary power sources, such as solar photovoltaic and diesel generation and storage. There are approximately 10 wind turbines in production that could potentially satisfy the requirements of this configuration.

A study of overturning moment was conducted to determine the necessary foundation requirements for the various configurations. A requirement of a minimum factor of safety of 1.5 was applied to the overturning moment of each configuration, thereby providing bounds where additional mitigations (first outriggers, then earth anchors) were needed to ensure safe operation for both 20-foot and 40-foot container systems.

Future work may include field demonstration and evaluation of deployable wind systems, facilitation of opportunities between defense and disaster organizations and industry to foster technology development, and a more detailed evaluation of airborne wind energy systems for defense and disaster relief. Airborne wind energy systems are attractive for deployable scenarios due to a higher potential rated power per container and the stronger wind resources aloft.

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