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Scalability and Compatibility assessment of Airborne technology in Maritime Transport: a case of electricity generation on a vessel

By

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Abstract

The Maritime industry is facing a challenge in reducing its dependency on fossil fuels. New regulations established to reduce the GHG emissions by maritime transport, force sector stakeholders to apply measurements and study new technologies for propulsion and electricity generation on board of seagoing vessels. Generally, wind energy is a source freely available in the oceans. New developments in the wind industry are working towards high altitude wind turbines, also known as Airborne Wind Energy Systems (AWES). These systems have gained significant ground with the availability of high performance and lightweight tether material, computational power, and advanced control technologies. However, applications of this technology in the Maritime industry are limited to ship propulsion only. Additionally, there are no scalability studies of Airborne Wind Turbines as electricity generators on board of a vessel. Therefore, the objective of this thesis is to develop a scalability and compatibility model for airborne wind technology for electricity generation on board of a ship. To achieve this goal, a case scenario based on the current 30 KW prototype of Kitemill and the FSU Njord Bravo have been studied. The stage of this technology as electricity generation on board, according to the Technology Readiness Level (TRL), is stage 2 – technology concept and/or application formulated. This means that the simplified models presented in this thesis lead to valid and reliable results for this phase of technology design. On one hand, the scalability model developed indicates that the traction force is the most critical parameter for the scalability of the Airborne Wind Turbine (AWT). On the other hand, the compatibility model shows that there is a notorious complexity in merging airborne and ship technology due to their context. Consequently, this research appears to be relevant for both, the industry developing airborne technology and the maritime industry. Lastly, this thesis provides a foundation for future research in this innovative application.

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“*MUCHAS GRACIAS DE TODO CORAZÓN*”

Dunia A. Domínguez Santana
Stavanger, 3rd of June 2019.

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List of abbreviations

AWES: Airborne Wind Energy System,
AWT: Airborne Wind Technology
DNV-GL: Det Norske Veritas Germanischer Lloyd
GA: General Arrangement
GHG: Greenhouse Gas
HAWT: Horizontal Axis Wind Turbine
HFO: Heavy Fuel Oil
IMO: International Maritime Organization
kg: Kilogram,
kW: Kilowatt
KW: Kilowatts,
m: meter,
MARPOL: International convention for the prevention of Pollution from Ships
MDO: Marine Diesel Oil
mm: milimeter,
MW: Megawatt
N: Newton
SEEMP: Ship Energy Efficiency Management Plan
SOx: Sulphur Oxides
VAWT: Vertical Axis Wind Turbine,
VTOL: Vertical Take-off and Landing,

List of Symbols

A= wing reference area of a kite/ aircraft
A_T= Tether cross- sectional area
b= velocity vector in figure 6
c= velocity vector in figure 6
C_D= Kite coefficient of drag
C_L= Kite coefficient of lift
D= wing span
D_k= Kite drag
D_P= power production drag
D_T= Tether diameter
D_w= Winch drum diameter
F_C= crosswind kite relative lift
F_D= crosswind kite relative drag power
Fs=simple kite relative drag power
F_{Cmax}= maximum F_C
g= acceleration of gravity
L= Lift of Kite
L_T= Length of tether
P= power produced
P_w= power density of wind
T= Traction force
V= kite velocity
V_A= relative velocity through air
V_C= velocity crosswind
V_L= load velocity
V_w= wind velocity
ρ= air density

Chapter 1

1. Introduction

1.1 Background and problem presentation

The shipping industry is considered the most energy efficient and least polluting of worldwide trading sector [1]. However, the international shipping emissions have been growing steadily which negatively affect the climate change. The International Maritime Organization has been for decades actively developing measures and regulations to reduce and control the greenhouse gas emissions (GHG). Thus, ship operators and owners are facing a challenge to be compliant with the mandatory technical and operation measures stipulated on Annex VI of MARPOL, where the SOx and CO_2 emissions limit is 0.50 % m/m, in contrast with the current fraction 3.50 % m/m [2]. These actions shall result in an expected reduction of pollution of 20% in 2020 and 50% by 2050 [3].

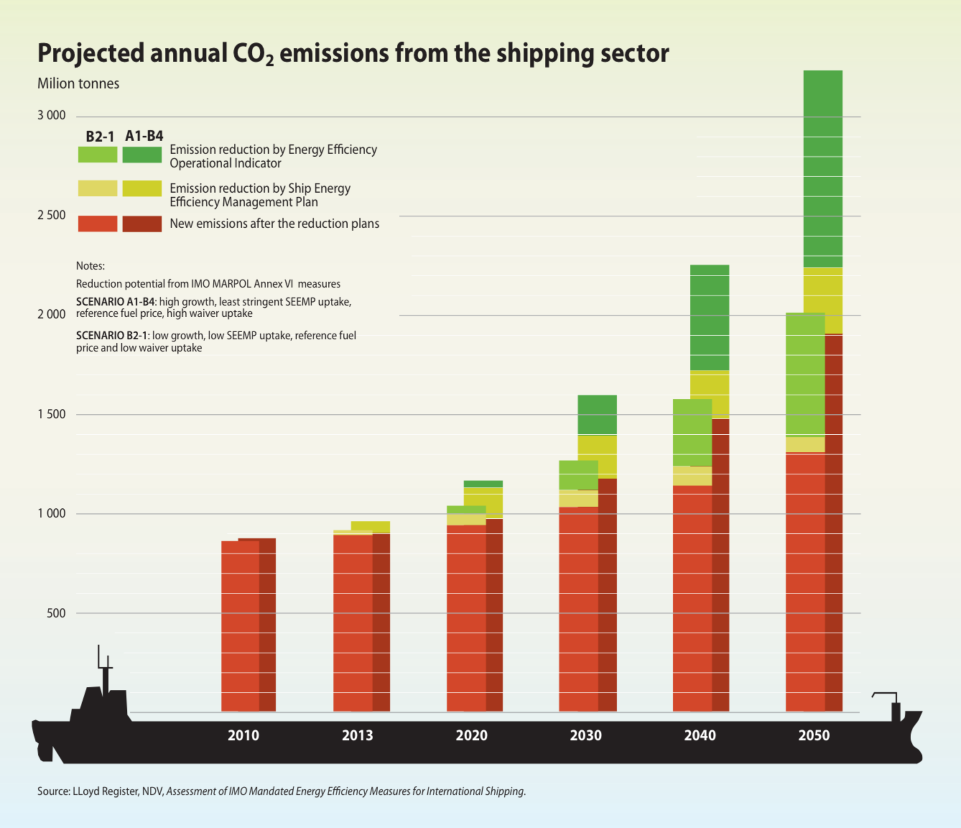


Figure 1. Projected Annual CO2 emissions. Source: Lloyd Register

The energy source for the propulsion has undergone significant transformations over the last 150 years, starting with sails through the use of coal to heavy fuel oil (HFO) and marine diesel oil (MDO).

In order to meet the IMO targets several strategies in energy efficiency need to be considered. In this regard, operational and technological measures have been developed not only by the IMO but also by researchers of the maritime industry.

One relevant tactic is the Ship Energy Efficiency Management Plan (SEEMP). It is an operational approach that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner.

The SEEMP includes the best practices for a fuel-efficient operation for new and existing ships [4]. On the other hand, technological strategies have focus on the role that renewables energy can play for power generation on board. Thanks to supportive policies and incentives promoting research, innovation and proof-of-concept examples, developers are increasingly enhancing ship designs and proof- of- concept pilots demonstrating major savings in some applications [3]. The scheme below represents the potential sustainable energy sources in maritime transport.

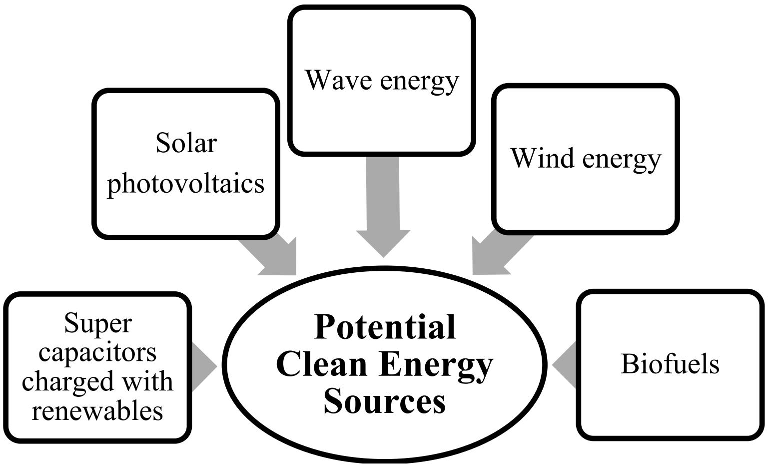


Figure 2. Potential Sustainable Energy in shipping scheme

Nowadays, there is a wide range of modern marine green technologies available on the market, used to improve the performance and sustainability of the oceangoing vessels. In general, all the energy sources mentioned in figure 2 have been explored and are, currently, in application development for maritime industry. It is worth to focus on the wind energy technologies achievement both in the maritime industry and inland applications.

Among the wind energy technologies shown on the figure 3, the only ones succeeding in the maritime transport are the Kites or Airborne wind technology, and the Flettner rotor in the applications in Beluga and Alcyone ships [5]. The wind turbines have not been considered further due to the dimensions and weight applicability on board oceangoing vessels [6].

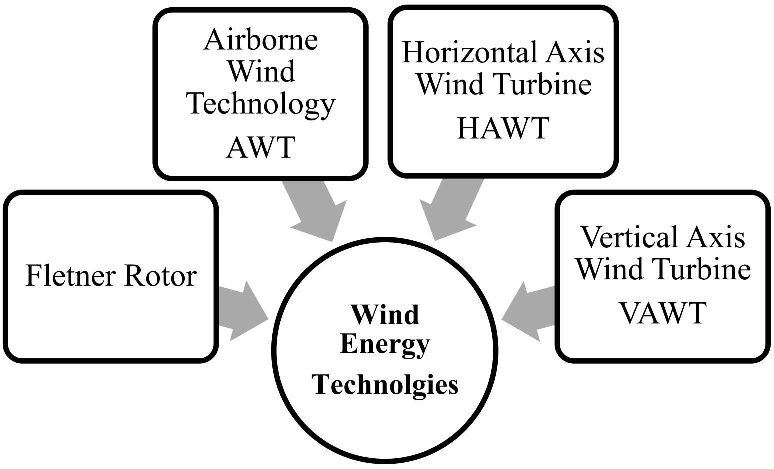


Figure 3. Wind Energy technologies

The Airborne Wind Technology (AWT) as a mean to harvest wind in high altitudes have been explored since the seventies. It is nowadays when clear advantages have been shown and prototypes have been developed to prove that Airborne Wind Energy Systems (AWES) are a feasible and competent solution to bare the worldwide emissions challenge [7].

The AWES consist of a ground system and at least one aircraft connected by a tether (rope). There are normally two different concepts:

- Ground- Gen AWES. The electrical energy is produced on the ground caused by a mechanical traction force [7].
- Fly- Gen AWES. The electrical energy is generated on the aircraft and it is connected by an electrical cable to the ground station [7].

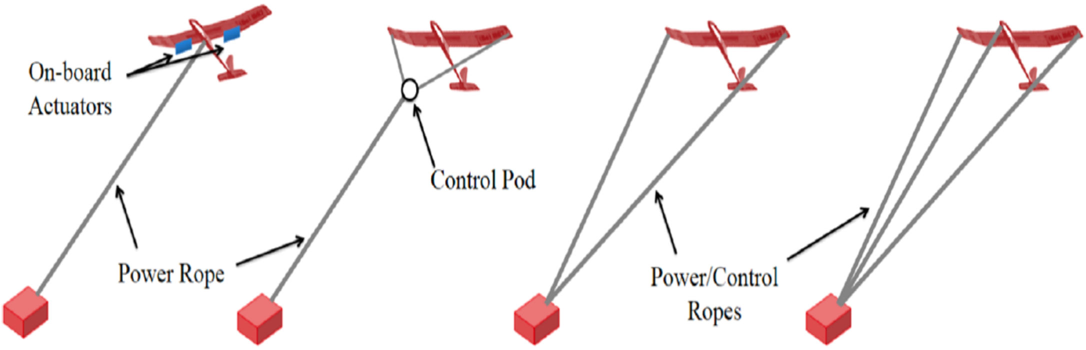


Figure 4. Ground-Gen AWES *[7]*

Several prototypes and patents confirm that Airborne Wind Technology has the following advantages [8]:

- Construction is very light and saves about 90% of the materials needed for the construction of a conventional wind turbine [8].
- The construction also allows AWES to operate at high altitudes, where the wind speed is higher and steadier than at lower altitudes. AWES can also alter their operating altitude, they can therefore always fly at the altitude were the wind velocity is highest at a certain point in time, which further increases steady energy production [8].

Developers and stakeholders of the wind energy sector are taking a rapid development in the designs and testing of this technology. In this trend, the Airborne technology is expected to lower the cost of energy and by 2030 it will grow further, according to Kitemill testimony.

To add up, the wind velocities offshore are also higher than inland, proving that there is a promising potential for airborne wind technology to generate more power on oceangoing vessels, since the power available is directly proportional to the cubed incoming wind velocity.

More than fifty organizations in industry and academia are involved in research and development in the AWES field today. AWES appear beneficial from both an economic and ecological perspective [9].

1.2 Research objectives and relevance

Various regulations are imposed on shipping to increase energy efficiency and reduce negative environmental impacts. Alternative power systems have been implemented or researched in order to achieve this target. This research will be based on the Airborne wind energy systems application in the maritime industry. In pursuance to supply energy from wind utilizing an Airborne Wind Turbine (AWT), there is a requirement of scaling- up and study the compatibility of installation in an oceangoing vessels.

Some of the studies and patents of the industry have worked towards Airborne wind technology as ship propulsion system, such as Sky Sails [10], Makani [11] and the studies of Michael Traut et al. [12]. Implementations on vessels with specific pattern of operation shall be performed to conclude in the contribution that this technology may provide.

Additionally, the research groups in the Airborne Wind energy based their studies in improving design aspects such as take- off and landing techniques [13] [14], airfoil design like rigid wing or soft kites, CFD and numerical modelling for power production [15].

Table 1. Research context

	Airborne Wind Technology	
	Propulsion support	**Electricity- generation**
Land Base	N/A	Kitemill Makani
Seagoing vessels	Sky Sails Makani	GAP

It exists a research gap within the industry in the following aspects:

- Lack of Scalability model rigid wings airborne wind technology as the current technology is limited to 30 Kw.
- Lack of Compatibility of installation of AWT as electricity generation on board of seagoing vessels
- Lack of implementation of this technology in ships with specific pattern of operation.

The fact of the Airborne wind technology is in design development and prototypes testing, presents an opportunity to explore the gap that currently subsists in the Airborne wind industry. The methodology presented in this research may provide a step towards closing the existing knowledge gap and stands ready to serve as a basis for further studies towards grasping the emission reduction in the maritime transport with the opportunities presented by AWT.

Therefore, this study aims to develop the scalability and compatibility models of a rigid wing Airborne technology energy to be used as a power plant in maritime transport.

1.3 Research question

How a rigid wing airborne could be scaled- up and compatible in a ship to generate the necessary electricity power demand on board of an offshore vessel?

1.4 Methodology

To asses if the rigid wing airborne might be installed on board of ship as electricity generation, a case study is implemented. The appropriate case study has to be such that covers the gap that is intended to be researched. Hence, an Airborne Wind Turbine prototype will be selected to be up-scaled and studied in terms of its compatibility in a vessel with specific pattern of operation in the Norwegian environment. The procedure is as follows:

1. Technical specifications of the Floating Storage Unit Njord Bravo are collected at Aibel Facilities
2. Technical specifications of the Airborne Wind Turbine are collected at Kitemill facilities.
3. Modification of crosswind kite power for scalability purpose
4. Development of compatibility model
5. Scalability Analysis
6. Compatibility Analysis

The figure 5, illustrates the procedure followed in this thesis.

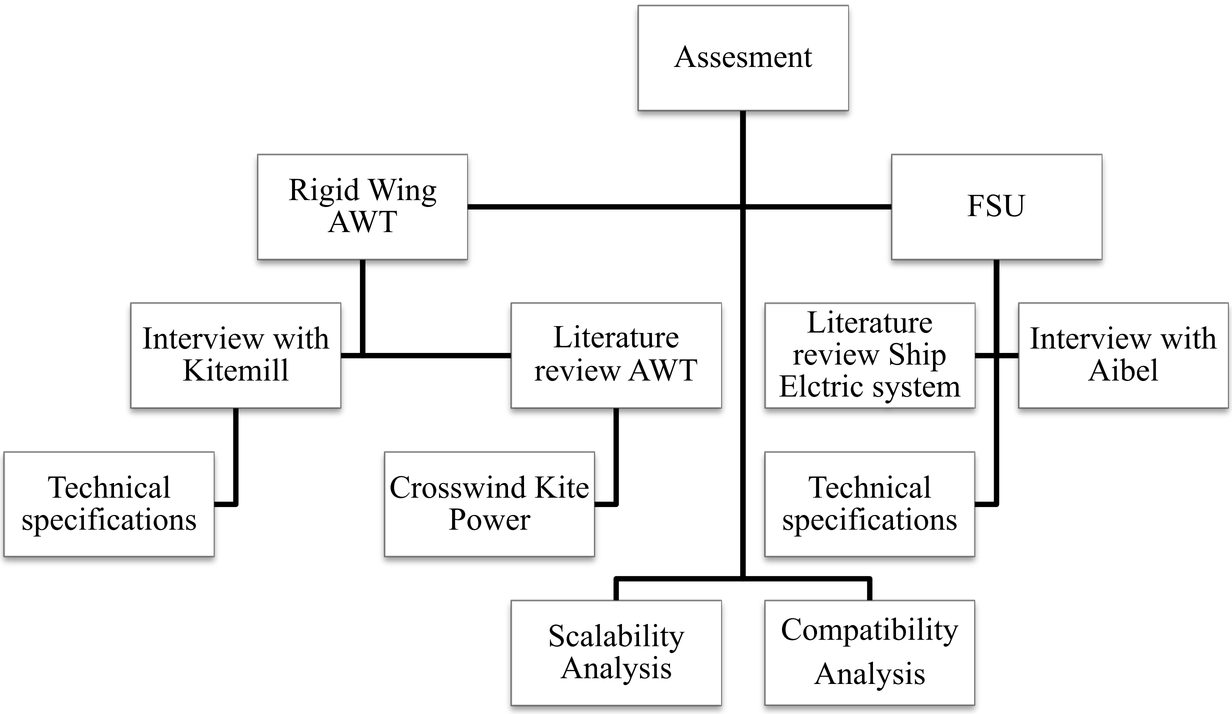


Figure 5. Thesis procedure

1.5 Scope of the thesis

The main scope of the thesis is to assess the scalability and compatibility of the application of a rigid kite into an offshore vessel for electrical power generation on board.

1.6 The structure of the thesis

The remainder of this study is organized in six chapters. The chapter 2 corresponds to the theoretical background; chapter 3 represents all data collected about Airborne wind Turbine and the Floating Storage Unit; chapter 4 shows the models development and the analysis; chapter 5 illustrates the discussion about the scalability and compatibility of the Airborne Wind Turbine in the Floating Storage Unit. Lastly, the chapter 6 embodies the overall conclusions of the study.

Chapter 2

2 Theoretical background

The theoretical background chapter represents an overview of the relevant theory that give basis to the present research. Thus, definitions for both AWES and Ship technology, as well as models and standards in use for this application are explained.

2.1 Theory about Airborne Wind Energy System

2.1.1 Relevant Definitions

High altitude wind. This is, wind fields from 100 m to 1000 m above the ground. Airborne wind Europe have provided high altitude wind maps above Europe, where it is confirmed that steadier and stronger winds appear to be at 500 m. On the region of North Sea and Baltic Sea the wind speeds at 500 m is about 10 m/s and above, but far offshore wind speeds are exceeding 12 m/s [8].

Crosswind power. Energy harvested by a kite/AWT that fly transverse to the direction of the wind field.

Wind Power Output. The wind power output is the power harvested by a commercial HAWT/VAWT or AWT, depending on the dimensions of the turbine itself and the wind speed of the place where the equipment is installed.

Tether. The tether is the component of the AWES that connects the aircraft/kite to the ground station. It is the most critical part of the system together with the airfoil. Its design carries how much traction force can be converted into electricity. In the case of ground- based AWES.

Wing Span. The wing span of an airplane/aircraft is the measured wing length from tip to tip [16].

Vertical Take-off and landing (VTOL). Capacity of some airplanes to perform the take-off (stop keeping contact with the ground) and landing (contact with the ground) in vertical manner using propellers with perpendicular axis to the wing (drone technology) [17].

Ground Station. The ground station of an AWES is the equipment converting the mechanical energy produced by the kite flying into electrical energy. It is form basically by a trawling winch and an alternator [17].

Traction force. In terms of AWES, the aircraft produces a tractive force when flying crosswind that pulls the tether at which it is connected to. This pulling force produces a torque in the trawling winch, and it is converted to electricity [18].

Load velocity. The load velocity is the velocity of the winch drum produced by the flying AWT [19].

2.1.2 Current developments of Airborne Wind Energy Systems

As mentioned before the AWES are divided into two types of power generator systems: Ground-Gen and fly- Gen. The tables 2 and 3 illustrate the current developments of both types accordingly.

Table 2. Ground-Gen AWES *[7]*

Ground- Gen AWES						
Ground Station	**Airborne System**	**Company**	**Power Class**	**Main Force**	**Actuator**	**Number of ropes**
Rail Ground station	Inflatable kite	KiteGeb Rail Carousel	MW-GW	Lift	On ground	2
		Kitenergy	MW	Lift	On ground	2
	Foil Kite	NTS	-	Lift	On ground	4
Axial Moving Ground station	Inflatable kite	KiteGen Carousel	MW	Lift	On ground	2
Ground Station	**Airborne System**	**Company**	**Power Class**	**Main Force**	**Actuator**	**Number of ropes**
Fixed ground station	Inflatable kite	KiteGen System	kW	Lift	On ground	2
		WindLift	kW	Lift	On ground	3
		Kitenergy	kW	Lift	On ground	2
		Swiss Kite Power 2	kW	Lift	On ground	3
		KitePower	kW	Lift	Airborne	1
		Swiss Kite Power 1	kW	Lift	Airborne	1
	Foil Kite	SkySails Power	kW- MW	Lift	Airborne	1
		EnerKite	kW	Lift	On ground	3

	Delta Kite	EnerKite	kW	Lift	On ground	3
	Swept Rigid Wing	EnerKite	kW	Lift	On ground	3
	Glider	Ampyx Power	kW- MW	Lift	Airborne	1
		e-Kite	kW	Lift	On ground	2
		Kitemill	kW	Lift	Airborne	1
	Glider with rotors	TwingTec	kW	Lift	Airborne	2
	Semi- Rigid wing	KiteGen Ste	MW	Lift	On ground	2
	Parachute	GuangdongTech	MW	Drag	Airborne	2
	Aerostat	Omnidea	kW	Magnus effect	Airborne	2
	Rigid Wing	Kitemill	kW	Lift	Airborne	1

Table 3. Fly-Gen AWES *[7]*

Fly- Gen AWES				
General System Description	**Flying principle**	**Company**	**Type**	**Emergency generation system**
Turbines on a tethered Aircraft	Wings lift	Makani Power	Crosswind	6/8 turbines
	Wings lift	Joby Energy	Crosswind	Several turbines
Tethered quadcopter	Rotors thrust	Sky Windpower	Non-crosswind	4 turbines
Turbine on a lighter than the air balloon	Buoyancy	Altaeros Energies	Non- crosswind	1 turbine
Magnus effect turbine	Buoyancy	Omnidea	Non-crosswind	Buoyant wind turbine

2.1.3 Crosswind Kite Power Model

A kite's aerodynamic surface (airfoil) converts wind energy into motion of the kite. This motion may be converted into useful power by driving turbines on the kite or by pulling a load on the ground. Some developments have converted the kite motion into useful work pulling a load on the ground with a tether [19].

The rigid wings kites would fly a closed path downwind from the tether point. The kite's motion would be approximately transverse to the wind. The crosswind airspeed of a kite with this trajectory is increased above the wind speed by the lift- to- drag ratio (L/D_k). The resultant aerodynamic lift[1] is sufficient to support a kite and to generate power [19].

---

[1] Aerodynamic lift: the component of aerodynamic forces acting on an airfoil acting opposite to gravity force.

The criteria for efficiencies of a kite are different for those used by Betz[2] [15]. The kite wing sweeps out a circular shape that may be compared to a turbine disk. If the slowing of the wind is small, the kite's efficiency will be lower than the Betz limit. The Betz limit that apply for Airborne wind turbine is 4/27 [15] .

2.1.3.1 Modeling

To support the dimensioning and scaling up the prototype used for this research the following model is used.

A kite is an aerodynamic vehicle restrained by a tether. Like an airplane, a kite produces lift ($\bar{L}$) and drag ($\overline{D_k}$) as it moves relative to the air. The kite is characterized by the reference area (*A)* of its wing, by its coefficient of lift (C_L) and by its lift- to- drag ratio [19].
In addition, the strength (*S)* of the kite must be sufficient to transfer the aerodynamic forces to the tether. This strength and the ratio of strength to weight (*S/W)* determine the necessary weight of the kite [19].

The tether is characterized by length (R), tether cross- sectional area (A_T), working stress (σ), mass density (ρ_T), and coefficient of drag (C_{DT}). The resulting drag of the tether is ($\overline{D_T}$) [19]. As the kite moves through the air, power may be generated by the tether traction force ($\bar{T}$) pulling a load at a velocity ($\overline{V_L}$) [19].

Power may be generated by an air turbine on the kite that adds a drag ($\overline{D_P}$)to the kite as it moves through the air at a velocity ($\overline{V_A}$). The total drag ($\overline{D}$) at the kite is the sum of $\overline{D_k}$, $\overline{D_T}$ and $\overline{D_P}$ [19]

2.1.3.2 Simple kite model

This simple model neglects the weight of the kite and the characteristics of the tether, including drag. In each case, the kite is assumed to have constant velocity. The power generated is expressed in terms of A, C_L, the wind power density (P_w), and a function (F) representing the specific model [19].

$$P = P_w A C_L F \qquad (1)$$

---

[2] Betz limit: theoretical aerodynamic efficiency of a HAWT is known to be 16/27.

Where the power density of the wind is

$$P_w = \frac{1}{2}\rho V_w^3 \tag{2}$$

A simple kite faces into the wind and remains static if the tether is restrained. Power may be generated at the ground if the tether unwinds from a drum. The forces and velocities at the kite are shown in the figure 6 [19].

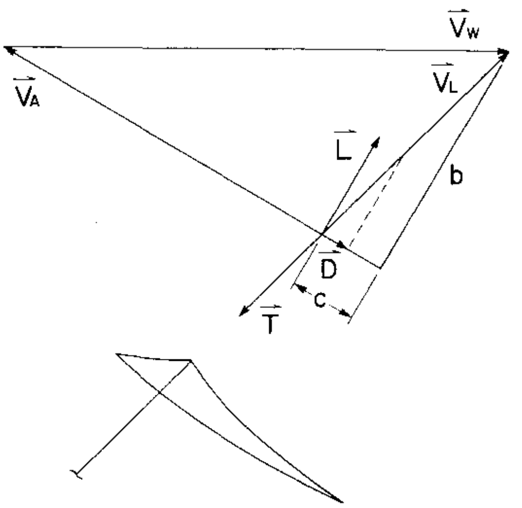


Figure 6.Forces and velocities on a weightless simple kite [19]

The power generated by this simple kite is

$$P=TV_L \tag{3}$$

Since the total drag (D) is D_K, and since L, D_K, and T form a right triangle,

$$T = L\sqrt{1 + 1//(\frac{L}{D_K})^2} \tag{4}$$

The lift is

$$L = \frac{1}{2}\rho C_L A V_A^2 \tag{5}$$

V_A is found in terms of V_w, L/D_K and V_L/V_w by analysis of the vector diagram in Figure 6. Extending V_A by c to the point where b is perpendicular to V_A forms a triangle with V_L that is similar to the one formed by L, D_K, and T [19], so that

$$\frac{b}{V_L} = L/T \tag{6}$$

Equations (4) and (6) give

$$b = V_L(\frac{L}{D_K})/\sqrt{1+(\frac{L}{D_K})^2} \tag{7}$$

Similarly,

$$c = V_L/\sqrt{1+(\frac{L}{D_K})^2} \tag{8}$$

From figure 6,

$$V_w = \sqrt{b^2+(V_A+c)^2} \tag{9}$$

Combining equations (3-5) and (7-9) and using V_w (V_L/V_w) for V_L given equations (1), where F becomes

$$F_S = \frac{V_L}{V_w\left[\sqrt{1+\frac{1}{\left(\frac{L}{D_K}\right)^2}-\left(\frac{V_L}{V_w}\right)^2}-\frac{\frac{V_L}{V_w}}{\frac{L}{D_K}}\right]^2}/\sqrt{1+1/(\frac{L}{D_K})^2} \tag{10}$$

2.1.3.3 Simplified crosswind motion model

Calculation of the power generated by a cross- wind flight mode kite is simplified as follows. In this simple model the weight of the kite and the characteristics of the tether, including drag are neglected. The power generated is expressed in terms of A, C_L, the wind power density P_w, and the function F, representing the specific model [19]. The final result is on the form:

$$P = P_w A C_L F \tag{11}$$

The magnitude of the relative wind velocity is V_W and the air density ρ.

Kites are commonly maneuvered by roll control. When one is flown to a position where the tether is parallel to the wind, the motion is directly crosswind. The speed through the air is increased above the wind speed, and the resulting power that may be generated is increased. The forces and velocities are shown in Figure 7 [19].

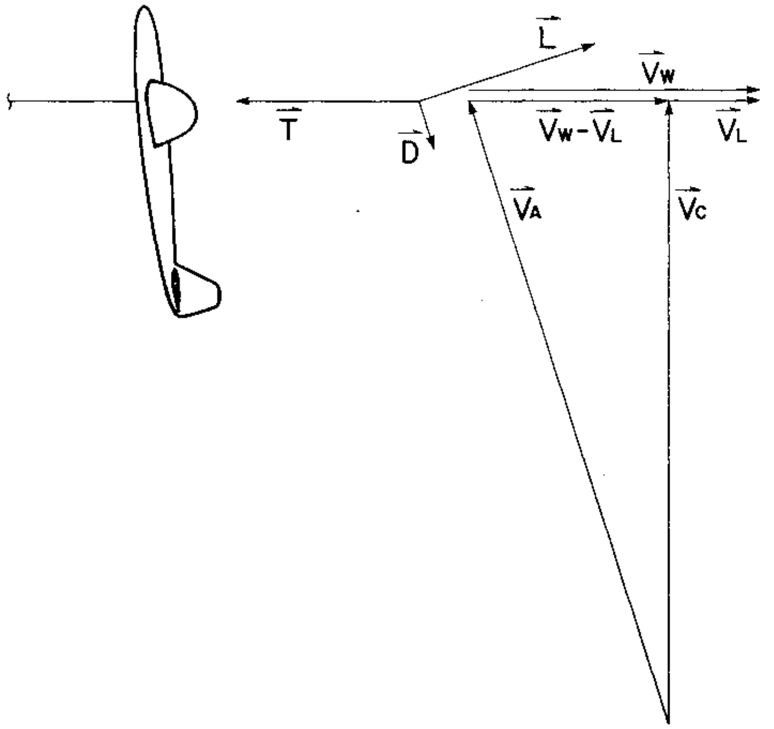


Figure 7. Aerodynamic forces on the AWE *[19]*

The total drag $\overline{D}$ is $\overline{D_k}$, $\overline{V_w}$ and $\overline{V_c}$ are the kite velocity, which is normal to the wind. Power is generated by pulling a load downwind at $\overline{V_L}$, so the effective wind speed at the kite is reduced to $\overline{V_w} - \overline{V_L}$. Since, $\overline{T}$ is parallel to $\overline{V_w}$, and $\overline{D_k}$ is parallel to $\overline{V_A}$, and since $\overline{L}$ and $\overline{D_k}$ are perpendicular and $\overline{V_w}$ and $\overline{V_c}$ are perpendicular, the velocities and forces form similar right triangles [19].

Thus,

$$V_C = (V_W - V_L)L/D_k \tag{12}$$

If L/D_k is large, $\overline{V_c}$ and $\overline{V_A}$ are approximately equal in magnitude so that

$$V_A = (V_W - V_L)L/D_k \tag{13}$$

The lift of the kite is given by

$$L = \frac{1}{2}\rho C_L A V_A^2 \tag{14}$$

Which becomes

$$L = \frac{1}{2}\rho C_L A[(V_W - V_L)L/D_k]^2 \tag{15}$$

Since $\overline{T}$ is colinear with $\overline{V_L}$, and the magnitude the power produced is

$$P = TV_L \tag{16}$$

However, the Lift and the Traction force are approximately of the same magnitude.

The function F becomes, F_C,

$$F_C = \left(\frac{L}{D_k}\right)^2 (\frac{V_L}{V_W})(1 - \frac{V_L}{V_W})^2 \tag{17}$$

The maximum value of Fc is

$$F_{Cmax} = \frac{4}{27}\left(\frac{L}{D_k}\right)^2 \tag{18}$$

Which occurs at

$$\frac{V_L}{V_W} = \frac{1}{3} \tag{19}$$

2.1.3.4 Simplified drag power model

When a crosswind kite pulls load downwind, as described above, it is essentially the lift of the kite that acts on the tether to produce power [19]. That mode of operation may be called lift power production. Power can also be produced by loading the kite with additional drag. Air turbines of the kite result in drag power [19].

Neglecting turbine losses, the power produced by air turbines adding a drag D_P [19], to the kite moving through the air at V_A is

$$P = D_P V_A \tag{20}$$

In Figure 7, the total drag D is the sum of D_K and D_P, and V_L=0, so equation (13) becomes

$$V_A = V_w L/(D_P + D_K) \tag{21}$$

Equations (5), (20) and (21) yield Equation (1), where F becomes

$$F_D = \left(\frac{L}{D_K}\right)^2 (D_P/D_K)/(1 + D_P/D_K)^3 \tag{22}$$

The maximum value of F_D is

$$F_{Dmax} = 4/27 \left(\frac{L}{D_K}\right)^2 \tag{23}$$

Which occurs at

$$D_P = D_K/2 \tag{24}$$

2.1.3.5 Findings

The results of the simplified crosswind motion are for a lift-to- drag of 10. For this simple analysis, the maximum lift power is equal to the maximum drag power.

The power produced by crosswind mode increases the square of L/D_K. With this model is found that a kite with a wing area of 576 m^2 and a minimum fuselage might have an L/D_K of 20. This kite will produce 22 MW in a 10 m/s wind. Actually, this is an upper bound that cannot be achieved because the motion cannot be purely crosswind, the tether has drag, and both the kite and tether have significant weight. Even so, approaching this potential power output seems very attractive for a single wind machine [19].

2.1.4 Theory for calculation of drum capacity model

A technical document developed by *Maxpull machinery and engineering Ltd* [20] is a good reference for the calculation of a winch drum capacity.

A winch is a mechanical equipment with one or more drum on which a cable or wire is coiled. It is used to pull or haul other devices. The drum capacity is the maximum length of wire rope that can be tightly evenly wound onto the drum [20].

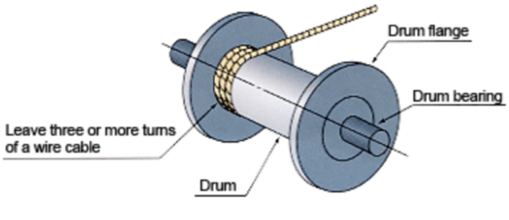


Figure 8. Winch illustration *[20]*

The length of wound wire rope onto the drum is established by the following equation:

$$L_i = \left[\pi\left(\frac{B}{d} - 1\right) \cdot (D_o + (2i - 1) \cdot d)\right] \qquad (25)$$

Where L is the length of wound wire; i is the number of layers (i=1, 2, 3…n); B is the width of the drum; d is the diameter of the wire; D_o is the diameter of the drum. The figure 9 shows the dimensions of the winch [20] .

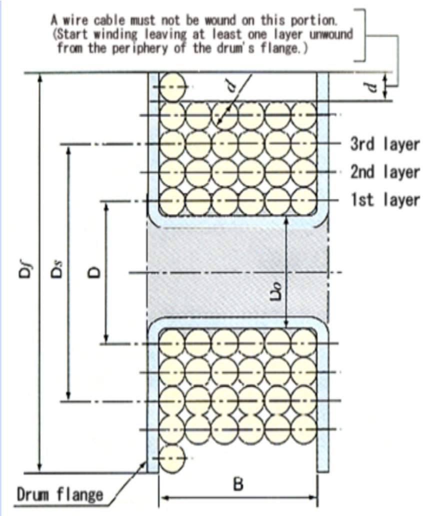


Figure 9. Winch Dimension parameters *[20]*.

DNV-GL regulations for Classification and Construction of seagoing vessel and offshore installations, support the principle described by *Maxpull machinery and engineering Ltd*. As general requirement, fiber ropes may be used for standing rigging and running rigging. Standing rigging refers to all wire ropes which are not turned round or wound on to winches whereas running rigging refers to all ropes passing over rope sheaves or guide rolls or wound on winches irrespective of whether or not the ropes are moved under load [18].

According to the DNV-GL regulation mentioned above on the Section 8:

C.3 Dimensioning: In the case of fiber ropes used for loading gear and loose gear, the breaking load F_{Br} shall not be less than the product of the static rope tension "F_S" and one of the safety factors "γ_F" given in Table 4:

$$F_{Br} \geq F_S \cdot \gamma_F \qquad (26)$$

Table 4. Safety Factor for standardized fiber ropes [18]

Nominal Diameter of rope [mm]	**Coefficient of utilization ·γ_F**
10-13	12
14-17	10
18-23	8
24-39	7
40 and over	6

In order to dimension the loading gear, such as the winch, the relevant rules are in the same section of the same regulations.

C.4.4 The required diameters of rope drums are to be agreed with GL in each case. For carbon fiber ropes, 12 d_s are to be taken.

C.4.5 The lateral deflection of fiber ropes relative to the plane of the groove of rope- sheaves or rope drums shall not be greater than 1:14 (4º).

C.4.6 The number of safety turns remaining on the rope drums shall not be less than 5. In case of synthetic fiber ropes a higher number of safety turns may be required

2.1.5 High Altitude Wind

The fact that the Airborne wind technology collect energy at heights beyond the reach of conventional wind turbines, AWE systems are exposed to different regions of the atmospheric boundary layer. The boundary layer consists of three different regions: a very turbulent mixed layer; less turbulent residual layer and a growing nocturnal boundary layer, which is randomly turbulent. The figure below shows the different boundary layers divisions [21].

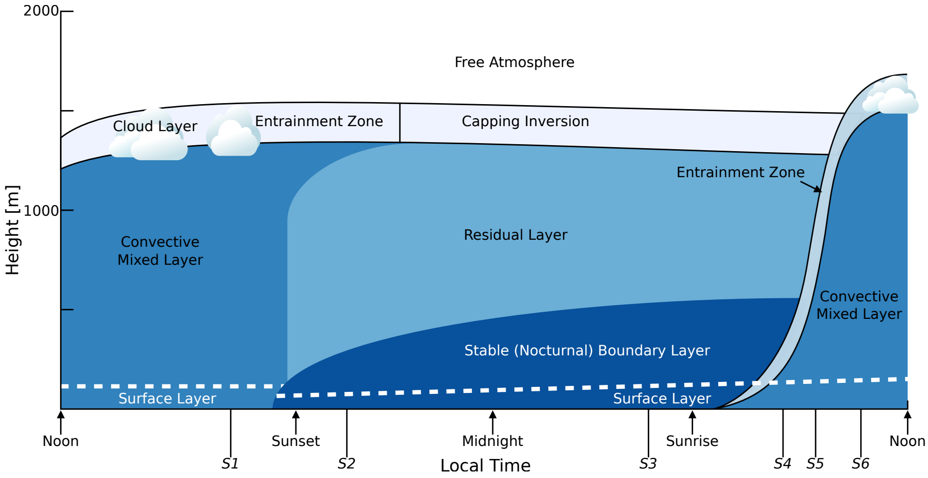


Figure 10. Boundary layer regions *[21]*

The first commercial AWE initiatives aim a maximum height of 500 m. Philip Betchle et al. [21] Assess the possibilities of adjusting the harvesting operation at higher altitudes. The study of *Airborne Wind Energy Resource Analysis* contributed to the industry producing high altitude wind maps, that show the average wind speeds at 500 m of altitude in Europe.

A comparison between wind speeds at 100 m and 500 m of altitude is shown on the figure 11. At most places onshore and offshore, the mean wind speed at high-altitude is at least 1 to 2 m/s higher than at 100m altitude [8]. Average high-altitude wind speeds exceed 10 m/s above practically all of the North Sea and the Baltic Sea and also onshore above all of the British Isles and Denmark and large parts of the Scandinavian Peninsula [8].Far offshore sites off the coast of Ireland boast mean wind speeds exceeding 12,5 m/s and even 13,75 m/s [8].

These findings show that when airborne wind energy devices are utilized local wind potential becomes much less of an aspect for deployment of wind parks, since most of Europe – onshore and offshore – becomes an attractive site for wind energy generation.

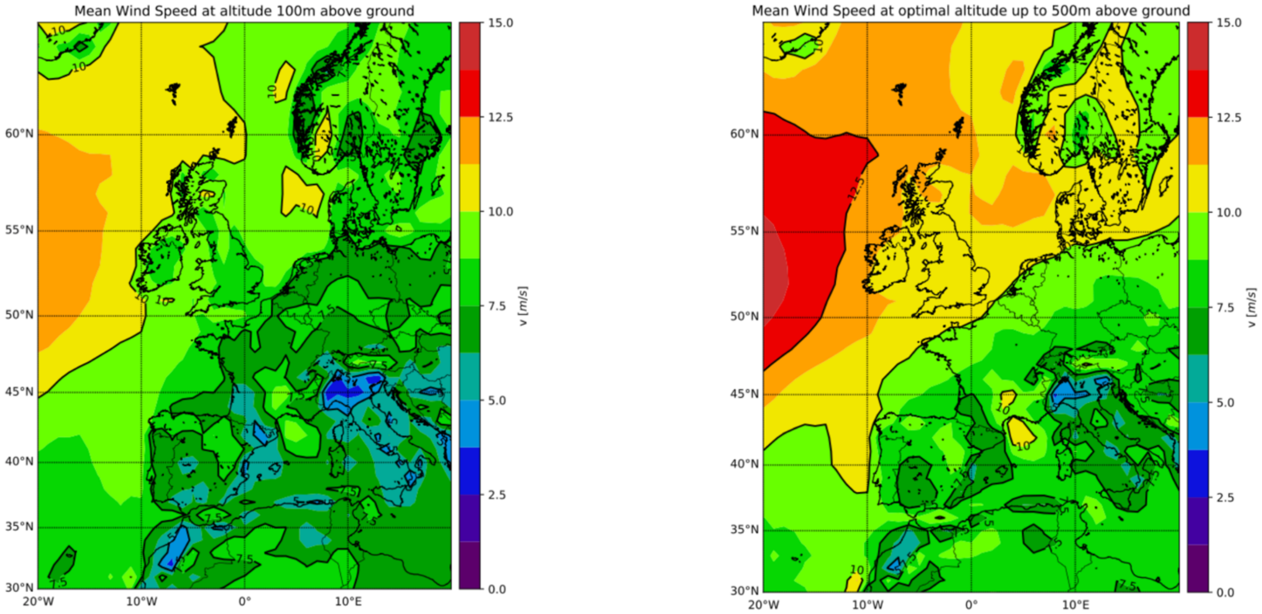


Figure 11. High altitude wind map *[8]*

2.2 Theory about the Ship

2.2.1 Relevant Definitions

Main Deck. As the name suggests, the main deck is the primary deck in any vessel. The main deck however is not the topmost deck in a vessel which is referred to as the weather deck. On sailing warships, it is usually the deck below the upper deck [22].

Upper Deck. The deck that covers the hull of the vessel from its fore to its aft is the upper deck. It is the topmost deck on a ship. In all vessels, the upper deck is the biggest deck amongst all other decks [22].

Poop Deck. Originating from the Latin term for a vessel's stern-side – *Puppis* – the poop deck is located on the vessel's stern. The poop deck is basically used by the vessel's commanding superiors to observe the work and navigational proceedings. Technically, it is the deck that forms the roof of a cabin built in the aft part of the superstructure of the ship [22].

Forecastle deck. A partial deck above the main deck at the bow of a ship over a forecastle.

Aft. Part situated at the stern of a ship.

Bow. Foremost part of a vessel.

Starboard. Nautical term used to locate the right-hand side of ship if a person looks towards the bow of the ship.

Portside. Nautical term used to locate the left-hand side of a ship if a person looks towards the bow of the ship.

Keel. The keel is the first element to build when building a ship. It resembles a fin and protrudes below a boat along the central line.

Design Draft. Is the measured from the keel of the vessel to the waterline.

Length overall (OAL). Is the longitudinal maximum length of a ship from aft to bow.

Moulded Breadth. Maximum transversal length measured from starboard to port-side.

Moulded Depth. Maximum vertical distance measured from the top of keel to the main top of the main deck.

Power supply installations. The power supply installations comprise all installations for generating, conversion, storage and distribution of electrical energy [23].

Auxiliary engine room. It is the room in the vessel that allocates the auxiliary engines for power supply. Normally, situated below the design draft.

Low voltage system. Are systems operating with rated voltages of more than 50 V up to 1000 V inclusive and with rated frequencies of 50 Hz or 60 Hz, or direct current systems where the maximum instantaneous value of the voltage under rated operating conditions does not exceed 1500 V [23].

Hazardous areas. Hazardous areas are areas in which an explosive atmosphere in dangerous quantity is liable to occur owing to local and operating conditions. Hazardous areas are divided into zones depending on the probability that an explosive atmosphere may occur [23].

2.2.2 Marine Auxiliary power plant

With the purpose of dimensioning the power plant of a ship, it is important to describe the common marine electrical system and define the elements that form it.

According to classification societies the electrical system of a commercial vessel is divided in two groups:

- **Main/Auxiliary power plant.** The auxiliary power plant provides electricity in normal operation conditions to all service needed on board such as pumping, motors, heaters, accommodation, maneuvering equipment, etc. [23]
- **Emergency power plant**. This plant delivers electricity to all essential services needed in extraordinary operation conditions to ensure the safety on board. These services are: firefighting equipment, navigation systems, emergency lightning, maneuverability equipment, watertight gates, etc. [23].

The figure below represents a standardized layout of a Marine power plant:

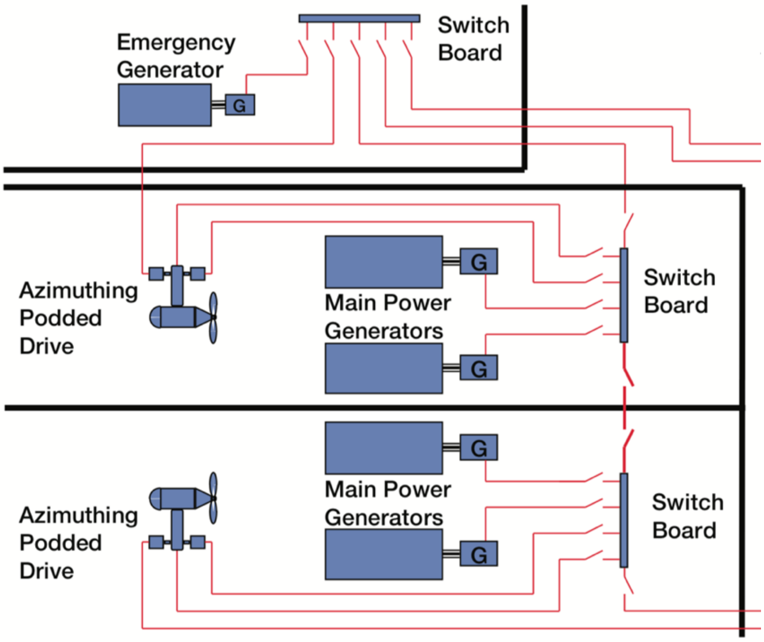


Figure 12. Marine Power plant. Source: Lloyds Register

On commercial vessels there are several services that have to be covered by the power generation on board. These services are classified as follow:

- **Non- essential services**. Those facilities whose failure do not affect the safety on board on emergency situations [23].
- **Essential services**. Group of electric consumers which are vital for the normal operation and maintenance of the vessel. The table 5 reflect the essential services connected to the auxiliary power plant [23].

Table 5. Essential services. Source: Lloyds Register

Servo drives	Firefighting pumps
Fresh and sanitary water	Lubrication pumps
Navigation systems	Bilge pumps
Feeding water pumps	Heating and domestic cooling
Circulation and cooling water pumps	Air compressors
Fuel pumps	Habitability
Navigation lights	Windlasses
Propulsion and safety equipment	Separators
Sprinkler system	Turbo blowers
Fan room machines	Fans cooling load services

- **Emergency services**. Equipment that have to function perfectly in emergency situations [23].

Table 6. Emergency Services. Source: Lloyds Register

Evacuation stations	Navigation aids
Emergency lighting	Alarm systems
Local servo	Emergency fire pumps
Bilge and Firefighting equipment	Heating and domestic cooling
Navigation lights	Servomotor
Internal and external communication	Watertight doors
Navigation lights	Sprinkler system

When analyzing the power plant of a ship is important to consider the following operation conditions:

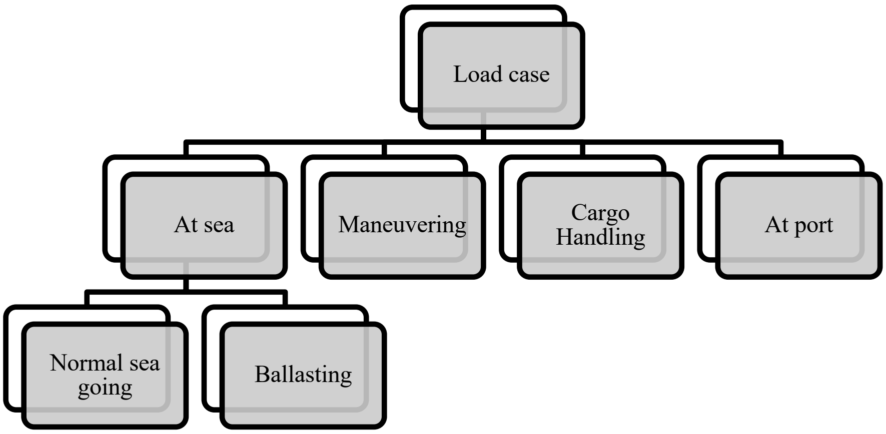


Figure 13. Operational conditions of a vessel

In every operation each consumer functions at different load factor, so that the total consumption of energy varies from one load case to another. Once consumers are listed and the energy consumption of each for every operation condition is analyzed the total energy consumption on board may be estimated, therefore the plant shall be dimensioned accordingly.

2.2.2 Standards for Installation of Electrical Equipment on board a vessel.

According to the Rules and Regulations for Classification and Construction of seagoing ships, by Germanisher Lloyd [23], to install electrical equipment on board the Section 2 of this standard have to be compliant. In this, point the relevant rules to apply are defined.

A.1 Main generator. The main generators shall be installed in the main engine room or in a particular auxiliary machinery room.

B.1 Main generators with their own prime movers, independent of main propulsion plant.

B.1.2 Main generators may be installed in the fore ship only with special approval and subject to the following conditions:

- Generators shall not be installed forward of the collision bulkhead below the bulkhead deck.
- The installation shall ensure the faultless operation, even in heavy weather, particularly with regard to the supply of fresh air and the removal of exhaust air.
- The aggregates shall be capable of being started, connected, disconnected and monitored from the main switchboard.

B.3 Emergency generators and their prime movers shall be installed above the uppermost continuous deck and behind the collision bulkhead. Exceptions require GL approval. The location in which the emergency generator is installed shall be accessible from the open deck.

The section 3 of the same Regulations document by Germanisher Lloyd [23], refers to design of electrical power supply, this section states the following:

B.1.1 Every ship is to be provided with a main source of electrical power with sufficient capacity to meet the requirements of the plant.

B.1.2 The capacity of the generating sets shall be such that, if any one generating set should fail or be shut down the remaining generating capacity is sufficient to supply all those items of equipment which are needed, when navigating at sea, to ensure:

- Normal operational conditions of propulsion and safety of the ship
- A minimum of comfortable conditions of habitability
- Preservation of the cargo, as far as the equipment is part of the classification

Minimum comforts for living on board, include at least adequate services for lighting, cooking heating, domestic refrigeration, mechanical ventilation, sanitary and drinking water.

B.1.9 The ship machinery installations shall be so designed, that they can be brought to operations from dead ship condition.
“ Dead ship” condition means that the complete machinery plant including the main source of electrical power are out of operation and auxiliary energy as compressed air, starting current from batteries etc. are not available for the restoration of the main power supply, for the restart of the auxiliaries and for the start-up of the propulsion plant. It is however assumed that the equipment for start- up emergency diesel- generator is ready for use.

C.3.4.2 The transitional source of emergency electrical power shall be a storage battery which, in the event of failure of the main source of electrical power, automatically and immediately supplies the relevant consumers until de emergency generator set is put into operation and connected.

Chapter 3

3 Data collection

In this chapter a detailed description of the new technology and application are addressed. Further, the technical specifications of the ship where the case study is based on. The data collection has been performed with the following steps:

- Technical meeting to the Technical Manager of Kitemill in Lista.
- Technical meeting to the Construction Manager of the Njord Bravo at Aibel facilities.

3.1 Rigid Kite Description

The rigid kite is a technology currently in development as a system for electricity generation. This study focuses on the technology developed by Kitemill, a start-up company that aim to connect to the grid onshore using AWE equipment.

The system consists of:

1. **Aircraft.** Airborne technology, on the flight mode the aircraft generates a tractive force.
2. **Tether.** A fiber rope that transmit the tractive force generated by the aircraft to the ground system
3. **Trawling winch plus generator.** Convert the tractive force from the tether to electricity
4. **Control system.** It controls the vertical take- off and landing, the flight mode and the pitch of the wings to optimize the flight conditions and the energy generation.

A rough sketch of how the system look like is on the figure 14:

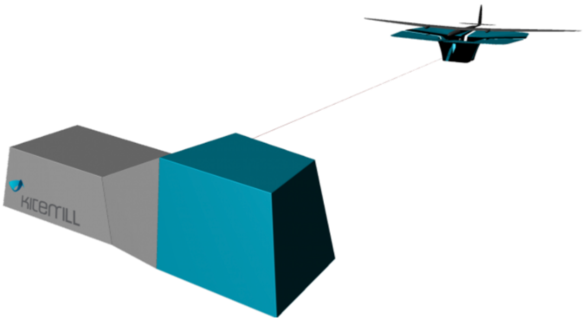


Figure 14. Kitemill technology sketch *[24]*.

3.1.1 Operation

The principle of AWE is based on the aerodynamic of traditional wind turbines. So that, the kite flies in circles as the blade tip of a HAWT, harvesting the wind energy available on the area it sweeps.

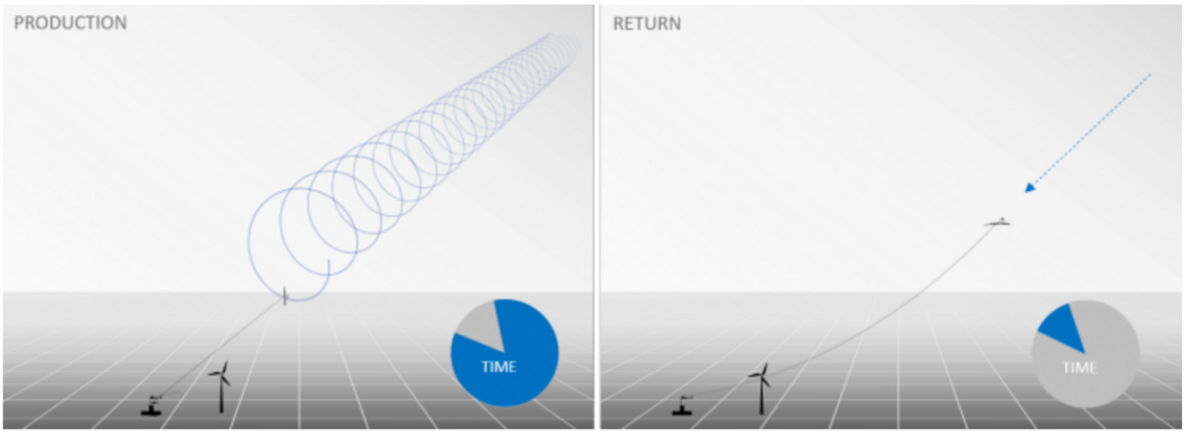


Figure 15. Kitemill AWT production *[24]*

A Kitemill is an electricity generator powered by the wind. The generator axle is equipped with a spool that stores a tether (rope), which is attached to a kite. Once launched the kite generates a tractive force transmitted by the tether to the generator. While flying away from the generator at approximately a third of the wind speed, unfolding a helical pattern, the kite spools out the tether which drives the generator [24]. When the tether is spooled out the kite starts flying back 'return path' to the generator that becomes a motor and spool the tether back in. In this stage the electricity is consumed [24].

Figure 16. Real operational mode of Kitemill 30 Kw. Source: Kitemill

The concept was evaluated by Det Norske Veritas (DNV-GL) in 2010 where the technology was proved to be feasible. Kitemill system follows the best practice procedure for technology qualification. The table 7 reflects the technical specifications of the 30 Kw Kitemill [19].

Figure 17. Kitemill Aircraft design

Table 7. Technical specifications of Kitemill AWT *[24]*

PART OF THE SYSTEM	DIMENSION	MATERIAL	DESCRIPTION
Kite	Wingspan (D): 7.5 m	Carbon fiber	Convert the wind energy into tractive force (lift) to the tether
Tether	Diameter (D_T): 2 mm	Polyethylene	Transmit the tractive force to the ground system (reel)
Winch	Drum Diameter (D_w):1 m Nominal Traction force (T): 7500 N Nominal reel speed (V_L): 4m/s	Steel	Switch between generator and motor mode
Generator	Nominal Power (P): 30 Kw	-	Direct Drive Ensure reel in/reel out speed
Control System VTOL	Number of propellers: 4 Simulator: Matlab/Simulink	-	Battery pack Navigation system Wind speed sensor Wind direction

Kitemill is working on improving and vanish the technical limitations in order to start producing with a demo park of five 30 KW Kitemill by 2020. The idea behind is to scale up and reach power output up to 2 MW and be commercially competitive by 2030.

Table 8. Technical Limitations of AWT *[25]*

Technical Limitations
Autonomous flight 2 hours
Navigational system is limited
In high centrifugal forces the sensors fail
Space design

3.2 Floating Storage Unit (FSU) Description

This section comprises the technical specifications of the vessel where the AWE application will be assessed.

Floating Storage Units are vessels moored next to a mother platform in order to storage the oil recovered from the well until it is offloaded onto a tanker, later on. The FSU to be described is currently in an entire refurbishment project in Aibel shipyard, Haugesund. The Njord Bravo FSU is planned to be in operation in October 2020. The FSU is connected to the platform Njord Alpha in the Njord field development operated by Equinor. This field is in the Norwegian sea and it is exploit at 330 m water depth.

Figure 18. Njord Bravo. Source: Marine Traffic

The Njord Bravo project is a total refurbishment in order to ensure the structural integrity after ten years in port. However, generators, thrusters have been extracted for overhauling and electrical cables and transformer will be replaced to comply with new standards that seek robustness of the systems.

The technical specifications are described on the table 9:

Table 9. Technical specifications of the FSU *[25]*

Characteristic	**Dimension**	**Unit**
Name	Njord Bravo	[-]
IMO	8766181	[-]
Ship Type	FSU	[-]
Tonnage	60750	[tons]
Deadweight (DWT)	95000	[tons]
Overall Length (OAL)	232.6	[m]
Breadth Moulded	41.50	[m]
Depth Moulded	23.75	[m]
Design Draft	15.50	[m]
Accommodation	8	Crew member
Propulsion System	N/A	
Dynamic Positioning	2	Thruster
Power Plant capacity:		
Main Power generator	1x1880	[Kw]
Fire pump generator	1x800	[Kw]
Emergency generator	1x335	[Kw]

3.2.1 Operation

Generally, the FSU has not propulsion system, meaning that is towed to the operation field. The thrusters are exclusively used for keeping the position for safer offloading operations while connected to the mother platform and the tanker. In terms of power generation, the mother platform provides high voltage and it is transformed to low voltage to provide electricity to the equipment on board, mainly for accommodation facilities, control equipment as well as heating equipment in the storage tanks.

It is worth to outline the cases where the ship consumes most of the electricity. This is normally used to establish the power demand on board, and the energy balance of consumers in each of the load cases. Most of the essential equipment operate in every load case. However, the higher power demand is presented in Offloading and in the journey to the field.

The figure 19 shows an overview of the load cases of the electricity generation plant of the FSU Njord Bravo.

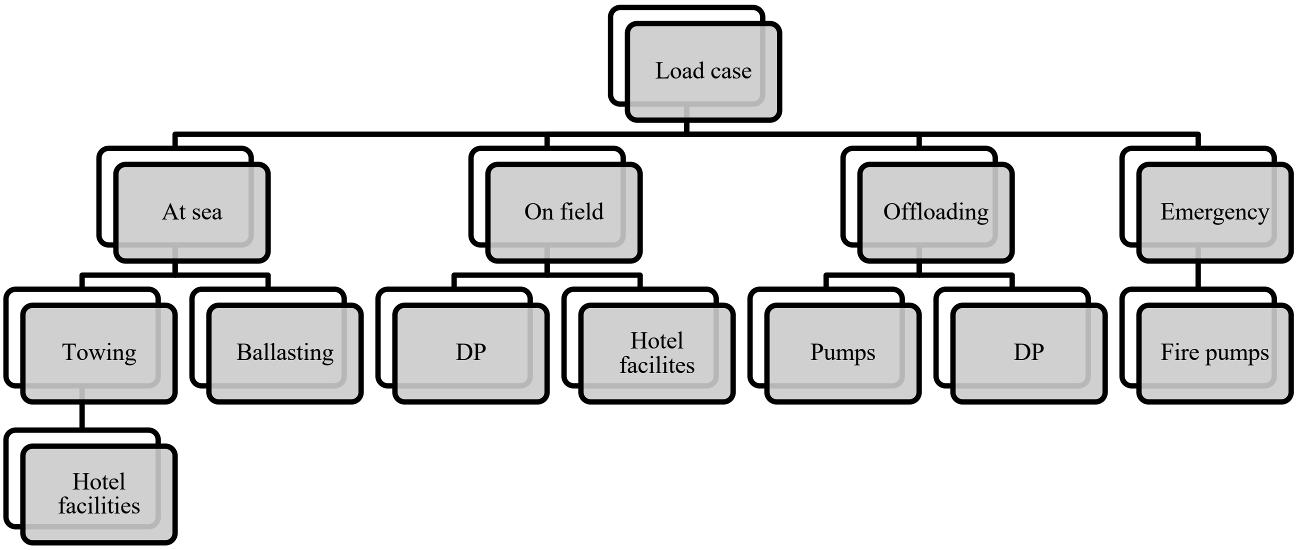


Figure 19. Operation modes of FSU Njord Bravo

Chapter 4

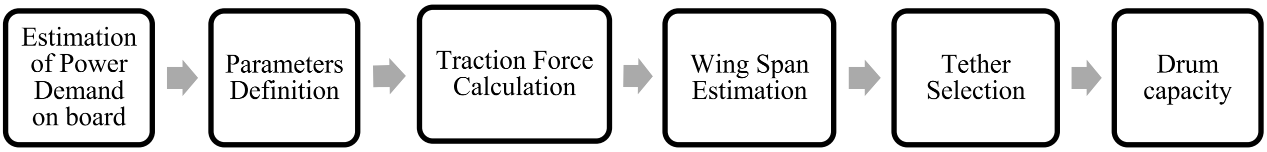
4. Scalability and Compatibility Analysis

The section 4 represents the development and analysis of the models used to assess the scalability and compatibility of the AWT as power plant in the maritime sector. The subsections completing this section are:

- AWT Scalability model analysis
- AWT installation compatibility model analysis

4.1 Scalability model development and analysis

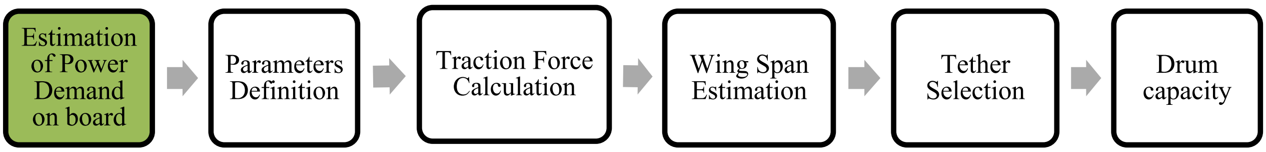
In first place, in this case study, the first purpose is to scale up the 30 KW AWT designed by Kitemill. To do so, the following model which is based on the Crosswind kite Power Model developed by Lloyd [19] is proposed:



The model is divided in six steps, each of them is developed in order to achieve the desired AWT that should satisfy the power demand on board the FSU Njord Bravo. Thus, the model will follow the steps below:

- Step 1. Estimation of Power demand on board
- Step 2. Parameter definition
- Step 3. Wing span estimation
- Step 4. Traction Force Calculation
- Step 5. Tether Selection
- Step 6. Drum Capacity

4.1.1 Step 1: Power demand on Njord Bravo



The ideal case will be to replace the power plant of the FSU by an AWT. Nevertheless, just the replacement of the main generator is studied in this thesis. The Njord Bravo have three generators. All of them have different capacities therefore they are installed for different purposes as it is shown on the table 10.

Table 10. Power installed in Njord Bravo

Generator	Capacity [3]	Purpose	Load Cases
Main Generator	1880 Kw	Normal operation conditions: Kitchen, ballasting pumps, monitors, alarms, cameras, communication system, Navigation system, lights, heating system, thrusters.	At sea On field Offloading
Fire pump generator	800 Kw	Firefighting equipment when pressure of sea water pumps is low. It is use in case of fire on board.	Emergency
Emergency Generator	335 Kw	Communication, Navigation system, DP system, Navigation lights, emergency lights, alarms.	Emergency

---

[3] Note: All data have been collected from generator datasheets provided by the construction manager of Njord Bravo project at Aibel.

For this particular case it is a good approach to assume that the power consumed on board is around 60-70 % of the total capacity of the main generator. Since a generator must not run more than 30 minutes at its maximum capacity. With this assumption a safety margin of 40-30 % is considered.

Due to the uncertainties related to weather forecast and wind conditions, it is safer that the emergency and fire pumps generators are kept as diesel generators with the use of efficient equipment and scrubbers, in order to avoid excessive GHG emissions.

Thus, the power demand on board considered from the main generator is:

$$\boldsymbol{P = 65\ \%\ of\ 1880 = 1222\ KW}$$

If 1.22 MW are consumed on board, as a safe approximation, a power of 1.5 MW shall be considered so the kite produces more than the current consumption installed on board.

$$\boxed{\mathbf{P \approx 1.5\ MW}}$$

It is important to note that the power demand is assumed to be constant and equal than the power output of the kite.

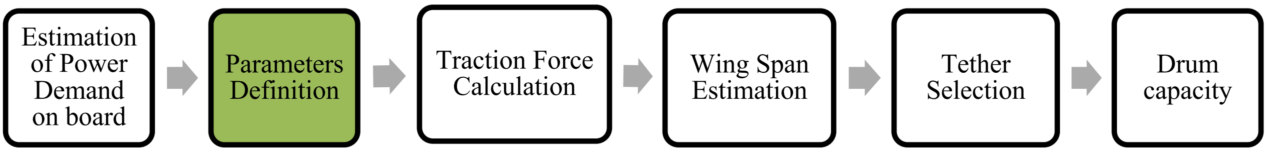
4.1.2 Step 2: Parameter definition

Once the power consumption on board Njord Bravo is estimated, the AWT designed by *Kitemill* must be up-scaled in order to provide the energy demand on board. The table 11 illustrates the current Kitemill design specifications.

Table 11. Current kite design parameters. Source: Kitemill

Parameter	Value	Unit
Wingspan (D)	7.5	[m]
Tether Diameter (D_T)	2	[mm]
Drum diameter (D_W)	1	[m]
Power output (P)	30	[KW]
Traction force (T)	7500	[N]
Wind speed (V_w)	12	[m/s]
Reel or Load speed (V_L)	4	[m/s]

In this research a simplified model developed by Miles L. Lloyd [19] will be used to scale up the current kite parameters in order to fulfill the power demand on board.



In this step, all design parameters are defined and addressed in tables 12 and 13. However, it is worth mentioning several assumptions to justify the value of some input parameters.

- Assumption 2.1: lift- to- drag ratio values for kite airfoils vary from 7 to 10, the most common values used for Kitemill airfoil design are from 7 to 9, but in several design models value is 10 [15] & [26].
- Assumption 2.2: the most common value used for lift coefficient is 1 [19].
- Assumption 2.3: optimal wind speed for kite power production from 4 to 12 m/s [17].
- Assumption 2.4: according to the crosswind kite power simplified model the load velocity is assumed to be one-third of the wind speed, so that $V_L = \frac{1}{3} V_w$ [19].
- Assumption 2.5: The motion of the kite and the vessel are neglected.

Table 12. Input parameter for scalability model

Definition	**Parameter**	**Value**	**Units**
Lift- to- drag ratio	L/D_k	[7,10]	[-]
Lift coefficient of the kite	C_L	1	[-]
Crosswind kite relative lift power	F_C	[-]	[-]
Atmospheric Air density	ρ	1.2	[kg/m^3]
Wind velocity	V_w	[4,12]	[m/s]
Load velocity of the tether	V_L	1/3 of V_w	[m/s]
Maximum theoretical power coefficient *[15]*	C_{pmax}	4/27	[-]
Tether length	R	[250-1200]	[m]
Power output[4]	P	1.5	[MW]

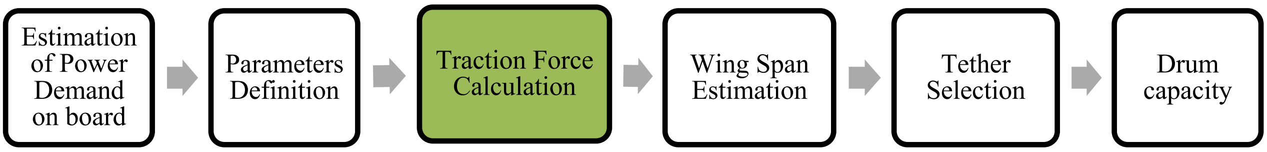
---

[4] Power output should be at least equal to the power demand on board.

Table 13. Output parameters after scalability model 1,5 Mw.

Definition	Parameter	Value	Units
Wing reference area of a kite	A	To be estimated	[m^2]
Maximum Crosswind Function	F_{Cmax}	To be estimated	[-]
Lift of kite	L	To be estimated	[N]
Traction force	T	To be estimated	[N]
Relative velocity through air	V_A	To be estimated	[m/s]
Wing span	D	To be estimated	[m]
Tether diameter	D_T	To be estimated	[mm]
Spooler Drum diameter	D_w	To be estimated	[m]

4.1.3 Step 3: Traction force estimation



The next step comprises the calculation of the traction force needed for the dimensions of the wing span, tether diameter and drum capacities. The calculation of this force is not accounting the drag effect of the tether and it is the most critical parameter for power generation. The estimation is done with the equations listed below which are executed with the software excel. The following assumptions are contemplated:

- Assumption 3.1: The drag effect of the tether is neglected [19]
- Assumption 3.2: The weight of the tether is neglected [19]
- Assumption 3.3: The power output is considered to be purely from lift of the AWT [19]

Having a maximum power output [19] implies that:

$$\frac{V_L}{V_W} = \frac{1}{3} \qquad (27)$$

Taking the input values for the wind speed reflected on table 12 the load velocity values are obtained.

Replacing, the values on the equation (16), which relates the power output with the load velocity, for different wind and the power output of $1.5 \cdot 10^6$ Watts.

$$\mathbf{T} = \mathbf{P}/\mathbf{V_L} \tag{28}$$

Where T is the traction force (see assumption 3.3) of the kite and P the power output [19].

It is worth recalling the figure which represents the forces and velocities.

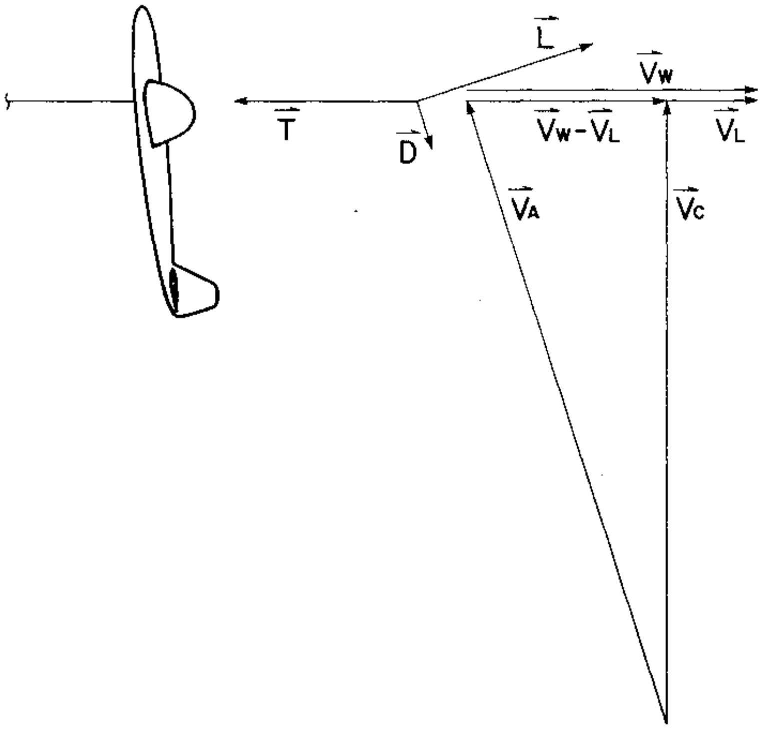


Figure 20. Kite Forces and Velocities *[19]*

The traction force $\overline{T}$ is opposite and presents a bigger magnitude than $\overline{V_L}$. If $\overline{V_L}$ increases in magnitude the Traction force $\overline{T}$ will be reduced.

It is important to note that Kitemill data have been provided for a wind speed of 12 m/s for the AWT of 30 Kw. Moreover, the data provided by the high-altitude wind maps [8] justify that taken this value is reliable for North Sea wind conditions at 500 m.

Therefore, the result of the traction force (T) at a wind speed of 12 m/s is:

$$\boxed{\mathbf{T= 375\ KN}}$$

The figure 21 shows the computed values of the traction force for wind speeds from 4 to 12 m/s. It illustrates that the traction force for a power output of 1.5 Mw is reduced when the V_L (1/3 of V_w) magnitude increases.

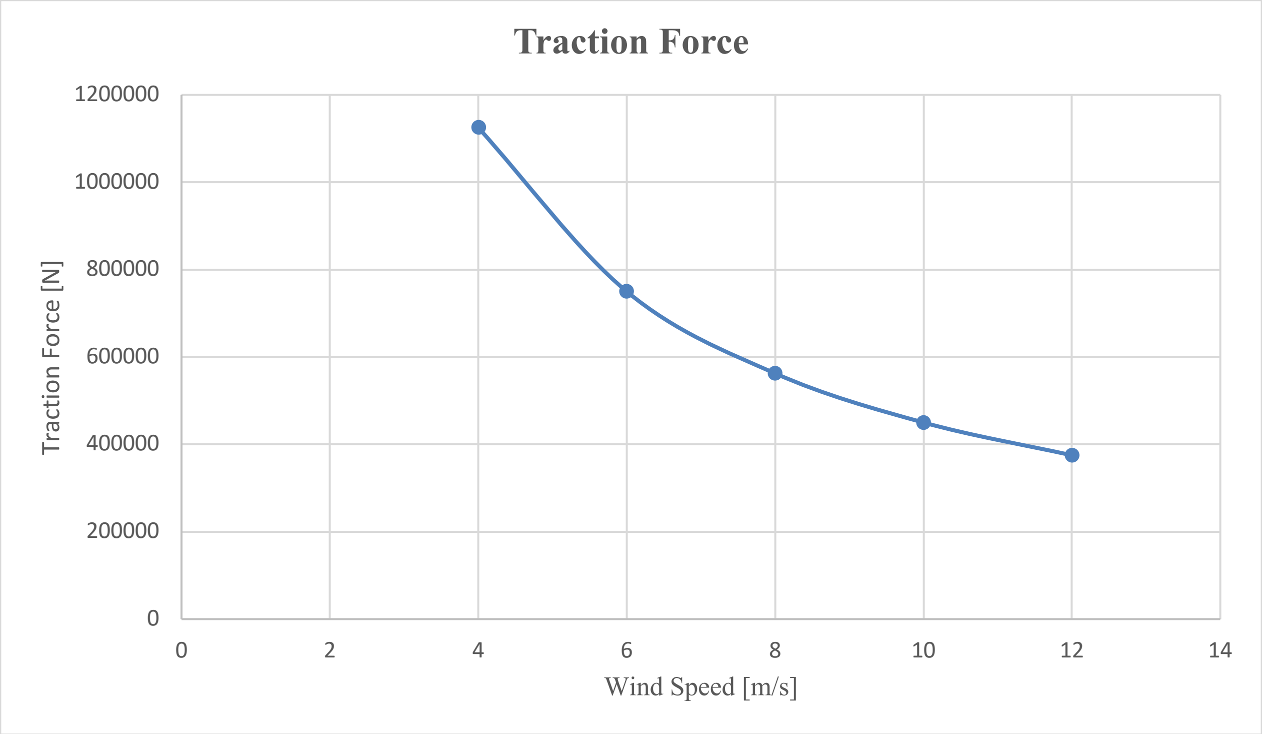
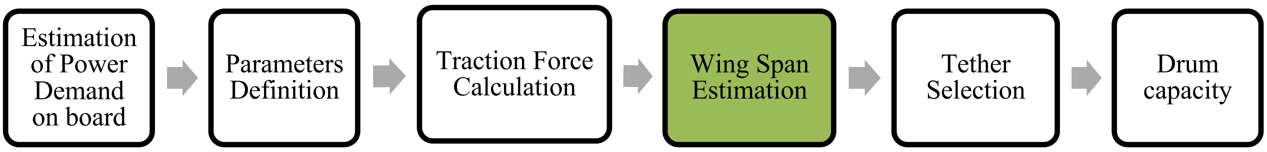


Figure 21. Traction force output for Lift to Drag ratio of 8

4.1.4 Step 4: Wing span estimation



With the intention of scaling- up the AWT, the main parameter to be estimated is the wing span. The wing span is the maximum extent across an airplane measure from tip to tip [16]. In the case of a kite or a normal HAWT, this dimension is related with the swept area.

For the calculation of the wing span, the aspects below will be assumed:

- Assumption 4.1. The width of the airfoil is neglected, only the aerodynamic surface is considered.
- Assumption 4.2. The swept area is considered is circle shaped.

From equation (14), which relates the Traction or Lift of the kite with the wing reference area of the kite, and the relative velocity, the area of the kite may be estimated.

$$L = \frac{1}{2}\rho C_L A V_A^2 \tag{29}$$

Rearranging the equation:

$$A = \frac{L}{1/2\rho C_L V_A^2} \tag{30}$$

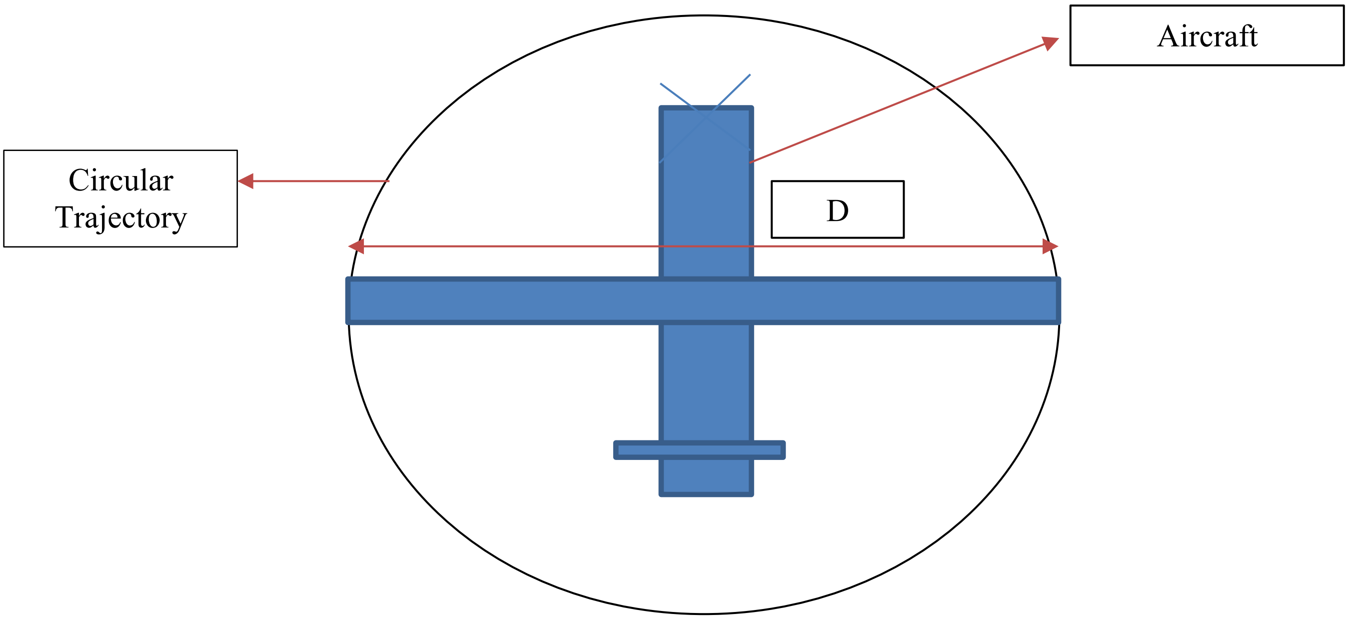
Where V_A is,

$$V_A = (V_W - V_L)L/D_k \tag{31}$$

If the flying kite have a circular path trajectory the wing span will be equal to the diameter of the kite path. Thus,

$$A = \frac{\pi D^2}{4} \tag{32}$$

Where D is the wing span.



For different values of lift- to- drag ratio, different V_A are calculated, therefore different wing reference areas are determined. Nevertheless, the wing span considered is at 12 m/s for a L/D =8 (see figure 22):

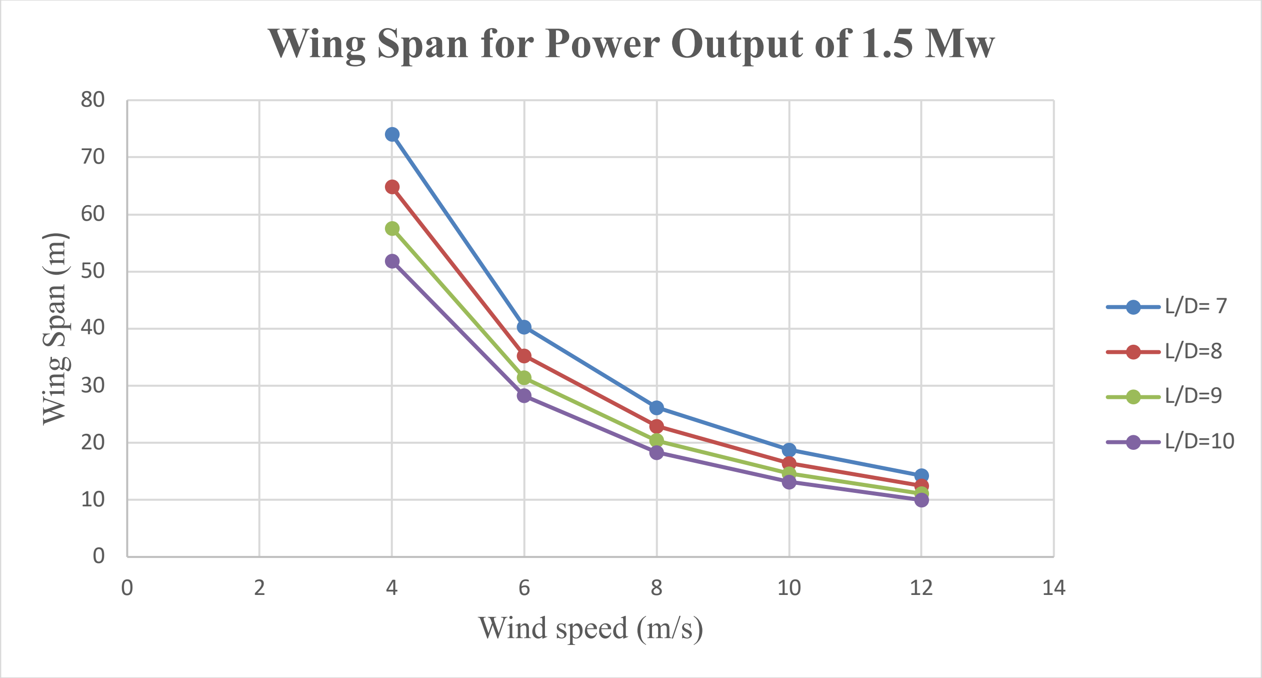


Figure 22. Wing span for different L/D coefficients

As it is seen, the higher the wind speeds, results in a smaller reference area (A) to harvest the kinetic energy of the wind. Consequently, the wing span will also be smaller as the wind speed increases. The average wind speed in North Sea region is 10 m/s and above.

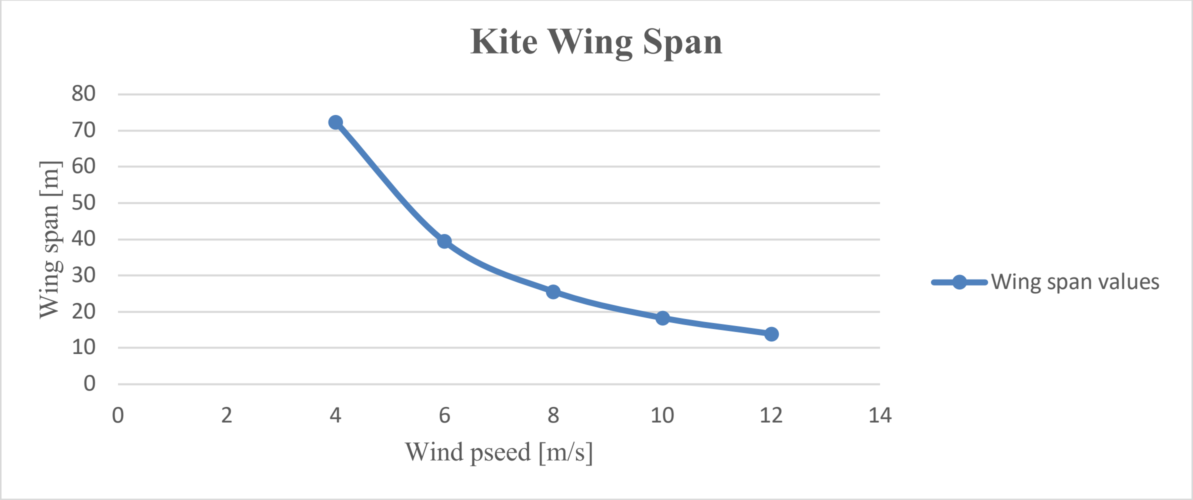
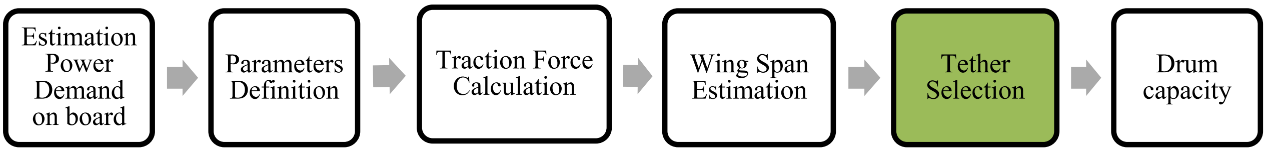


Figure 23. Wing span length

The computed value for the wing span at 12 m/s is:

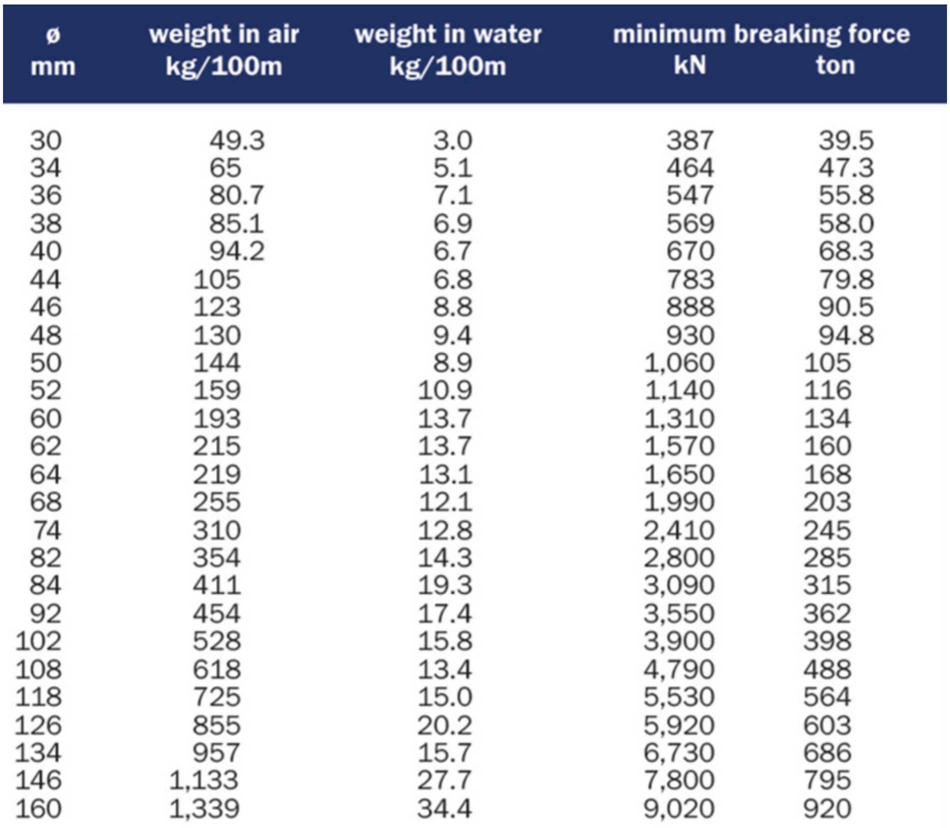
$$\boxed{\mathbf{D= 14\ m}}$$

4.1.5 Step 5: Tether Selection



It is out of scope of this study to make a detailed analysis of the tether and aerodynamic models of the system. Nevertheless, it is important to note for future studies that the tether drag have a big impact in the power output, the larger the drag of the tether the smaller the power output. That is why is recommended to follow a catenary model for the design of the tether and enhance the design aspects of the rigid kite.

It is known that for a kite of 30 Kw in a windspeed of 12 m/s, a traction force of 7500 N is generated for a tether with a diameter of 2 mm. The selection of the tether for this study will be based on manufacturers of synthetic fiber tethers for offshore applications. The preferred manufacturer is *Lankhorst Offshore* [27], which provide the options illustrated on the figure 24:



ø mm	weight in air kg/100m	weight in water kg/100m	minimum breaking force kN	 ton
30	49.3	3.0	387	39.5
34	65	5.1	464	47.3
36	80.7	7.1	547	55.8
38	85.1	6.9	569	58.0
40	94.2	6.7	670	68.3
44	105	6.8	783	79.8
46	123	8.8	888	90.5
48	130	9.4	930	94.8
50	144	8.9	1,060	105
52	159	10.9	1,140	116
60	193	13.7	1,310	134
62	215	13.7	1,570	160
64	219	13.1	1,650	168
68	255	12.1	1,990	203
74	310	12.8	2,410	245
82	354	14.3	2,800	285
84	411	19.3	3,090	315
92	454	17.4	3,550	362
102	528	15.8	3,900	398
108	618	13.4	4,790	488
118	725	15.0	5,530	564
126	855	20.2	5,920	603
134	957	15.7	6,730	686
146	1,133	27.7	7,800	795
160	1,339	34.4	9,020	920

Figure 24. Tether specifications. Source: Lankhorst Offshore

The technical specifications for the up- scaled kite tether to be met are the following:

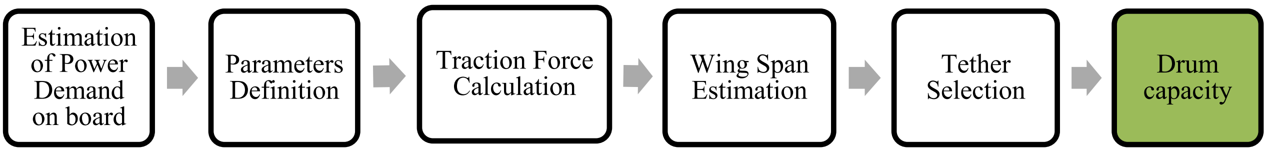
- Traction force estimated T= 375KN ≈37.5 ton
- Length estimated to be from 250 m to 1200 m
- Safety factor of 1.24 [18]

The most suitable solution is the first row of the table illustrated in the figure 24.

Therefore, the diameter of the tether shall be:

$$\boxed{\mathbf{D_T = 30\ mm}}$$

4.1.6 Step 6: Drum Capacity



Last step for scaling up the current design is the drum capacity since the winch is attached to the power generator. It is important to know the dimensions of the winch, so that manufacturers supply accordingly.

It is worth to recall the equation established by *Maxpull Machinery and engineering Ltd* [20]. The equation (25) have been implemented to calculate the winch drum capacity.

$$L_i = \left[\pi\left(\frac{B}{d} - 1\right) \cdot (D_o + (2i - 1) \cdot d)\right] \tag{25}$$

Where d is the same as the tether diameter (D_T)

The table 14 shows the input parameters which are in compliance with the DNV-GL Rules for classification and construction for loading gear on seagoing ships and offshore installation, section 8, C.4.4 and C.4.5.

Thus,

- The drum diameter has to be at least 6 times the rope diameter for polyester ropes [23]
- The layers to wind the rope onto the drum have to be at least 5 [23].

To compute the drum capacity let us assume that:

- Assumption 6.1: the drum diameter is 40 times de tether diameter (*Source: Kitemill)*

Table 14. Input Parameter for drum capacity estimation

Parameter	Value	Unit
Tether diameter: d	30	[mm]
Drum diameter: Dw	1200	[mm]
Width: B	1000	[mm]
N. of layers: i	10	[-]

Total capacity of the drum is:

L_T= 1523.67

The total capacity refers to the maximum length (L_T) tether the drum can allocate.

To sum up, the estimated values for optimal operation conditions of the kite at 12 m/s are represented on the table 15:

Table 15. Scaled-up prototype results

Definition	Parameter	Value	Units
Wing reference area of a kite	A	152	[m^2]
Maximum F_C	F_{Cmax}	9.48	[-]
Lift of kite	L	375000	[N]
Traction force	T	375000	[N]
Relative velocity through air	V_A	64	[m/s]
Wing span	D	14	[m]
Tether diameter	D_T	30	[mm]
Spooler Drum diameter	D_w	1.2	[m]

Overall, the table 16 compares the Kitemill current design characteristics versus the up- scaled proposal estimated in this section at optimal operation conditions.

Table 16. Comparison of 30Kw AWT vs 1.5 Mw AWT

Parameter	**Current prototype Value**	**Up-Scaled Value**	**Unit**
Wind speed	12	12	[m/s]
Reel speed	4	4	[m/s]
Power output	30	1500	[KW]
Traction force	7.5	375	[KN]
Wingspan	7.5	14	[m]
Tether Diameter	2	30	[mm]
Drum diameter	0.25	1.2	[m]

4.2 Compatibility model development and analysis

Firstly, in pursuance of assessing the compatibility of the AWT on board of the Njord Bravo for power it is worth to mention its context of application. In first place, the figure 25 shows the framework of the AWT in onshore development. Secondly, the figure 26 shows the environment of the Njord Bravo. These contexts will lately give basis for the discussion.

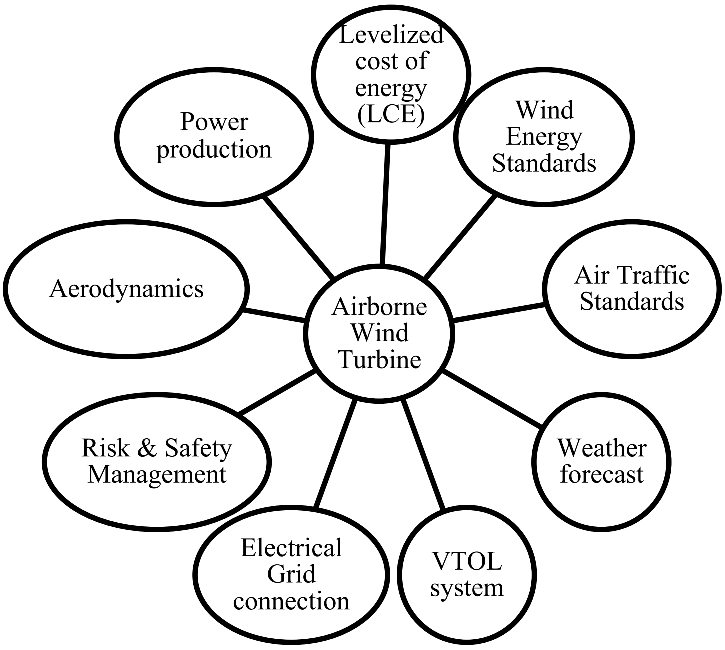


Figure 25. Airborne Wind Turbine context.

Figure 26. Njord Bravo Context

Once the AWT is scaled- up, the compatibility of the 1.5 MW rigid wing kite has to be modelled as follows.

The dimensions and location of installation will be asses dividing the model in three steps:

- Step 1: AWT Dimensions and Weight estimation
- Step 2: FSU Space availability
- Step 3: AWT Set up on board

4.2.1 Step 1: AWT Dimensions and Weight estimation

In this step, it is relevant to recall the shape and part that compose the AWT, and also note the dimensions and parts that have been scaled up for the application in the FSU Njord Bravo. The figure 27 shows the main components of the AWES.

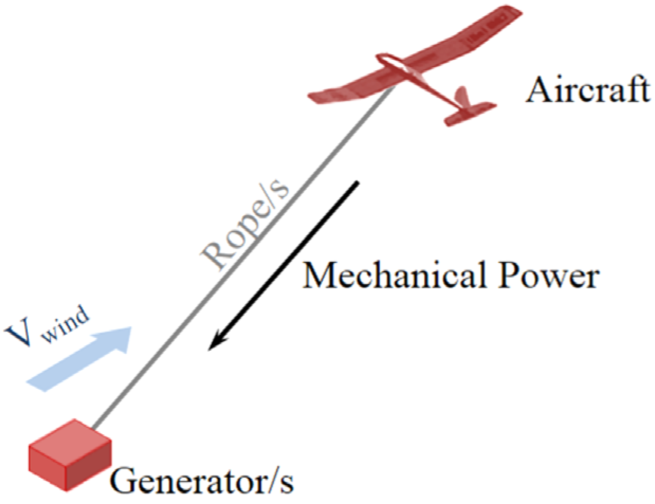


Figure 27. Ground Base AWES *[7]*

Thus, the dimensions and weight estimation will be split in four parts:

1. Generator
2. Winch
3. Rope/tether
4. Kite/Aircraft

1. Generator

The generator is the equipment that converts the mechanical rotational motion from the winch into electricity. The applicable generator for this case scenario able to provide 1.5 MW is the PI734B manufactured by Stanford Power Generation [28]. The figure 28 represents the technical drawing of the potential generator to be used.

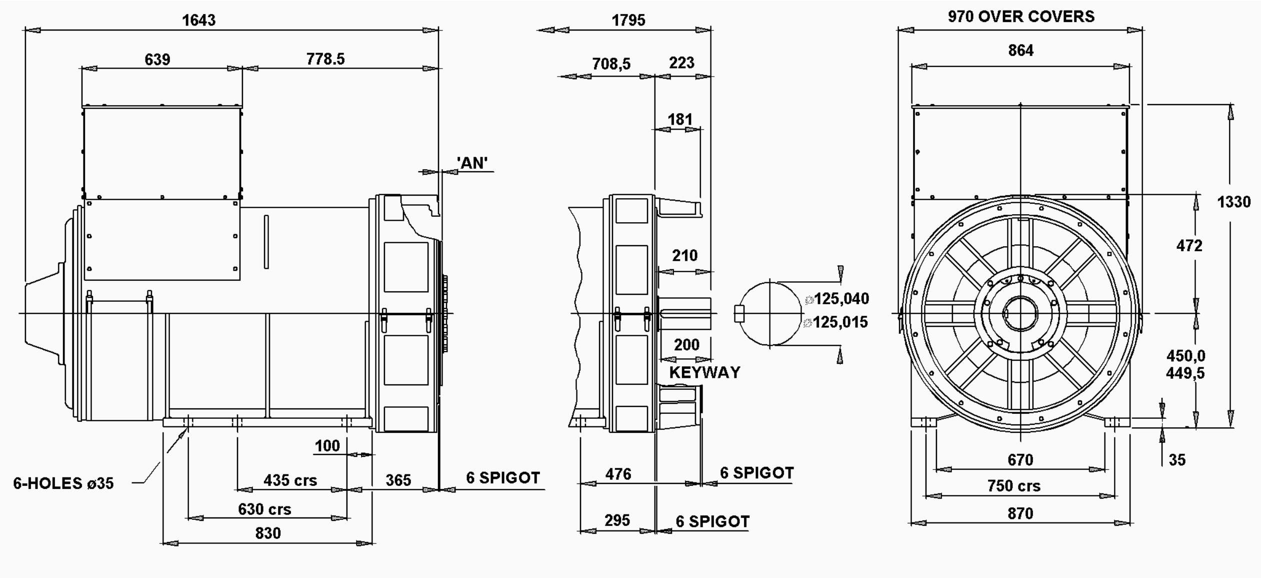


Figure 28. Generator technical drawing. Source: Stanford Power Generation

The main dimensions of the generators are illustrated in the table 17:

Table 17. Main dimensions of Generator

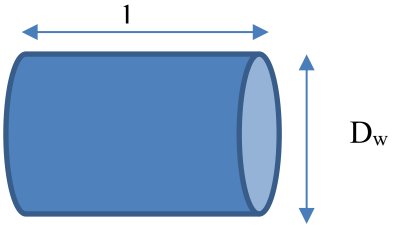
Component	Parameter	Value	Unit
Generator	Power	1,5	[MW]
	Length	1795	[mm]
	Height	1330	[mm]
	Diameter	970	[mm]
	Weight	5205	[Kg]

2. Winch

The winch is the component giving the mechanical work to the generator. It is the mechanism where the rope/tether is wind up.

Figure 29. Trawling winch used in AWES

Based on the calculations done in the section 4.2.6 the diameter and length of the winch drum were estimated. In order to calculate the weight of this component a cylindrical geometry will be assumed, and the material is carbon steel. Therefore, the computation of the weight is as follows:



$$V = \pi \frac{D_w^2}{4} l \tag{33}$$

$$m = \rho \cdot V \tag{34}$$

Where V is the volume; l is the length of the drum; D_w is the diameter of the drum; ρ is the density of carbon steel; m is the mass of the drum.

Table 18. Main Dimensions of the winch

Parameter	Value	Unit
Dw	1.2	[m]
l	1	[m]
ρ	7850	[Kg/m^3]
m	8878.14	[Kg]
Weight	8.88	[ton]

The specifications of the winch should be suitable to be connected to the generator and to accommodate a rope of 30 mm and have a capacity of at least 375 KN which is the traction force executed by the AWT at 12 m/s.

3. Rope/Tether

In accordance with the section 4.2.5 the rope/tether to be used in the scaled- up AWT have the characteristics shown in table 19. The mass of the rope per unit length have been calculated as follows:

$$A_{tether} = \pi \frac{D_T^2}{4} \tag{35}$$

$$m = \rho \cdot A_{tether} \tag{36}$$

Where ρ is the density of the fiber polyethylene; A_{tether} is the cross section of the tether; D_T is the diameter of the tether.

Table 19. Main Dimensions of the tether

Parameter	Value	Unit
D_T	30	[mm]
A_{tether}	$7.06 \cdot 10^{-4}$	[m^2]
ρ	880	[Kg/m^3]
m	0.62	[Kg/m]
L_T	1523.67	[m]
Weight	947.78	[Kg]

4. Aircraft or rigid wing kite

The aircraft is the critical component, this is the rigid wing kite that flights crosswind, to transform the kinetic energy from the wind with the aerodynamic surface, generating a traction force that is transformed ideally into 1.5 MW of power. In contrast with the current 30 Kw aircraft with 7.5 m of wing-span and 4 m length that weight approximately 35 Kg (source: Kitemill technical meeting).

The model used in the section 4.2 has result in a 1.5 MW aircraft of 14 m wing-span and approximately 8 m long, which weight will aim approximately to twice the current development, that will be between 70-90 Kg. This interval is because it has to account for both the propellers and the battery system on board the aircraft.

Table 20. Main Dimensions of the Aircraft

Parameter	Value	Unit
Wing span	14	[m]
Length	8	[m]
Weight	70-90	[Kg]

The electrical generation on board with the AWT has the following dimensions and weight:

Table 21. Total weight of the AWES as power plant

Component	Weight [Kg]	Dimensions [m]
Generator	5205	1.79x1.33x0.97
Winch	8878.14	1x1.2
Rope/tether	947.78	30x1523.67
Aircraft	70-90	14x8
Take off/Landing[5] Platform	-	16x10

4.2.2 Step 2: FSU Space availability

To study the space availability of the FSU Njord Bravo, Aibel has provided the General Arrangement (GA) of the ship.

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[5] The take- off/ landing platform will be 1 m longer in each side of the wings and 1 m aft/ bow of the aircraft.

In this research the possibility of replacing the FSU Njord Bravo power plant for an Airborne Wind Turbine has been studied. Consequently, it is reasonable to check the space availability on the deck and room where the current power plant is installed. If that is the case, then the power plant installation standards as well as stability matters might not be compromised.

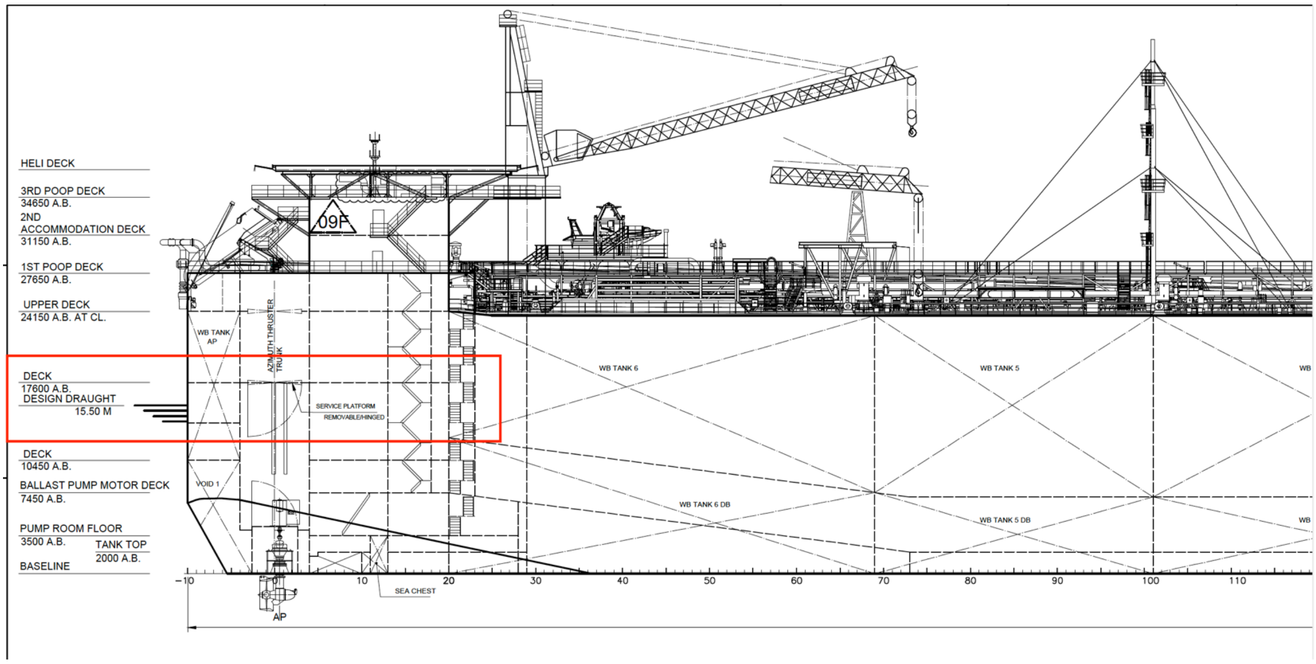


Figure 30. General Arrangement of FSU Njord Bravo. Source: Aibel

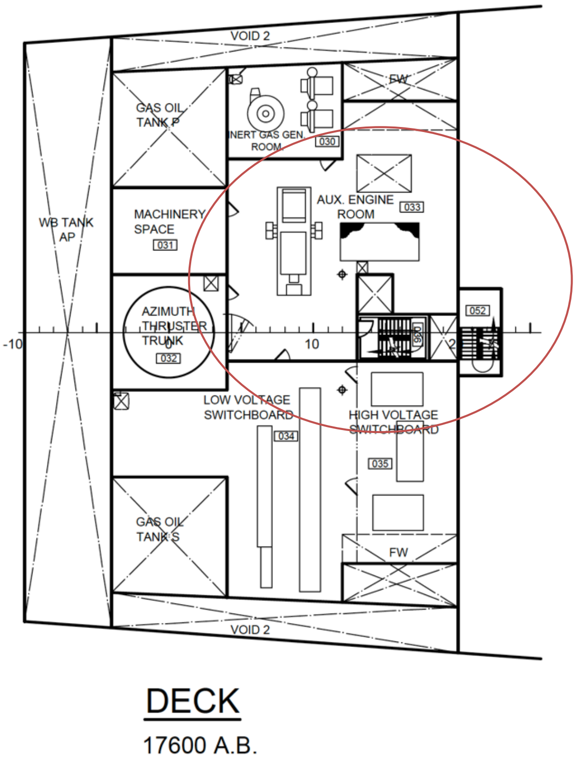


Figure 31. Deck lay- out of FSU Njord Bravo. Source: Aibel

The general idea is to place the generator together with the winch in the Deck 17600 A.B. where the Auxiliary power plant is currently placed (see figures 30 and 31). The dimensions of this room have been done from the GA, with a measurement stick then converting to a real scale 1:1, since the scale of the GA drawing is 1:300. So that,

Table 22. Measurements of Auxiliary engine room

Measurement	Value 1:300 [cm]	Value 1:1 [m]
Width from Portside to starboard	3.7	11.1
Length from aft to bow	4.2	12.6
Height	1.8	5.4

However, the aircraft should be placed on open space and in the highest point of the vessel. If that is the case, starting from highest to lowest, the sites available for the installation are: the 3rd Poop deck, the forecastle and the upper deck, respectively.

The chosen deck for installation is the 3rd Poop deck, since it does not interrupt other operations and the distance from the generator to the aircraft is the smallest compared with the other decks. The 3rd Poop deck has the following measurements:

Table 23. Measurements of Poop Deck

Measurement	Value 1:300 [cm]	Value 1:1 [m]
Width from Portside to starboard	8.5	25.5
Length from aft to bow	0.9	2.7

All the decks and parts of the Njord Bravo may accommodate all the components of the AWES. Nonetheless, several structural modifications on the ship might be needed.

4.2.3 Step 3: AWT set up on board

In the last step of the model a set-up of the AWT on board the FSU Njord Bravo will be proposed.

In the figure 32 the AWES is divided in three parts:

- Part 1: Generator and Winch
- Part 2: Steel pipe conducting the tether/rope
- Part 3: Take- off and Landing platform for rigid wing kite.

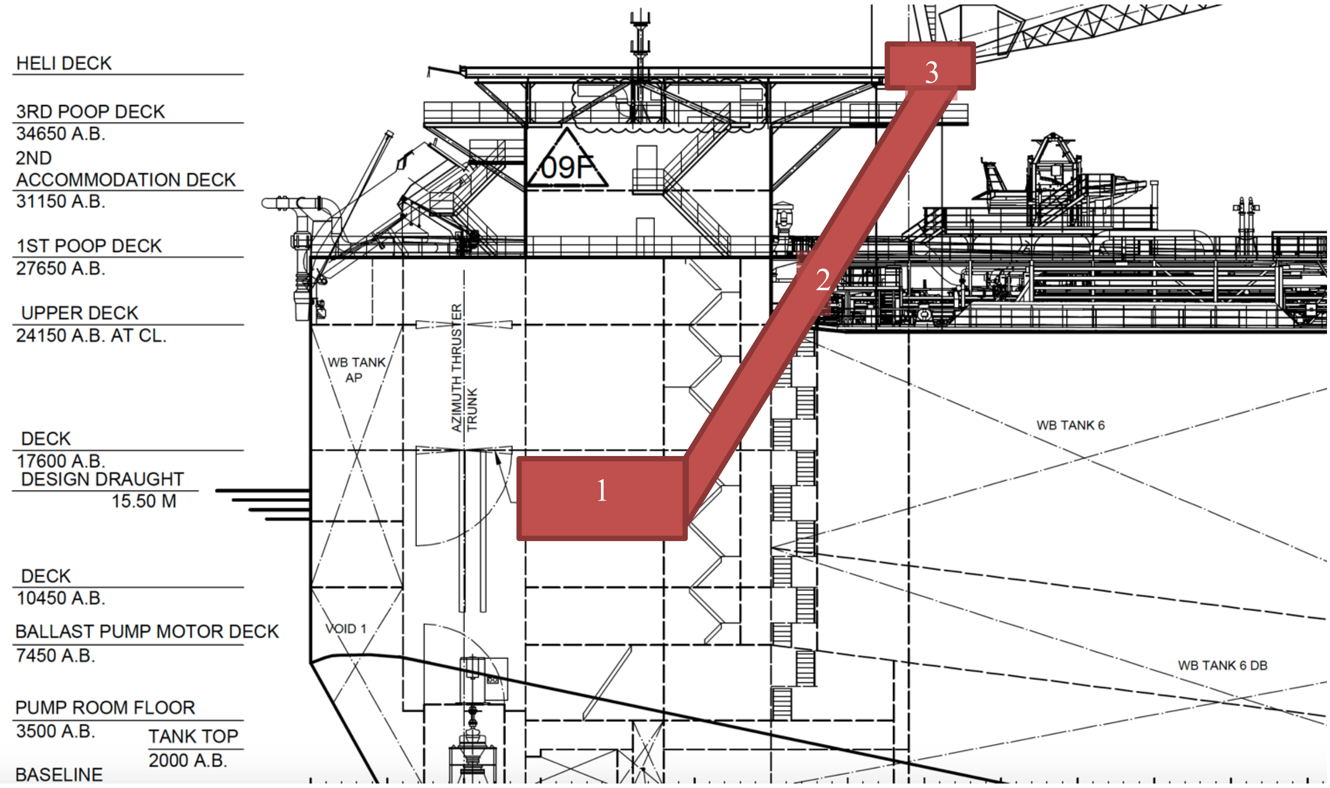


Figure 32. Proposed Set-up for AWES in FSU Njord Bravo

For this set up, structural adjustments in the ship should be performed as follows:

Firstly, the engine room may stay as it is since the dimensions of the equipment to be installed are smaller than the dimensions of the auxiliary engine room. Secondly, a pipe or conduct of at least 40 mm of diameter, starting from the winch position to the poop deck as shown on the figure should be built to make the tether pass through it and transmit the traction force.

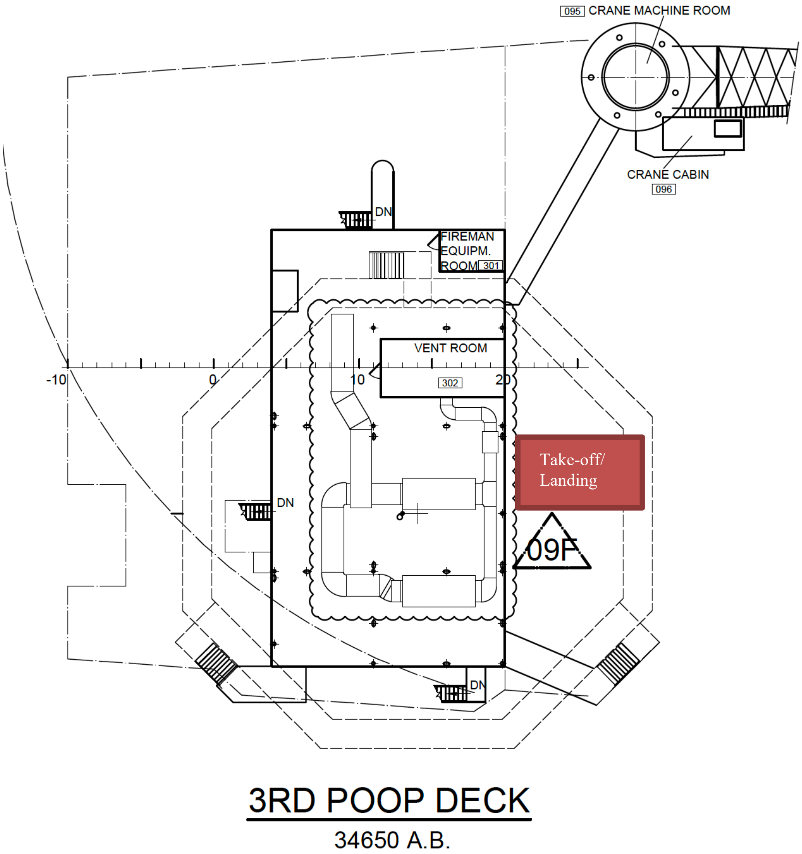


Figure 33. Poop deck lay out

Lastly, the outside area of the 3rd poop deck structure should be enlarged length wise, from 2.7 m to 11 m. Thus, the take- off /landing platform fit in the space between the edge of the helideck and the outside of the 3rd poop deck. Also, this deck should be strengthened to withstand the weight of the take-off/landing platform and the rigid wing kite.

Chapter 5

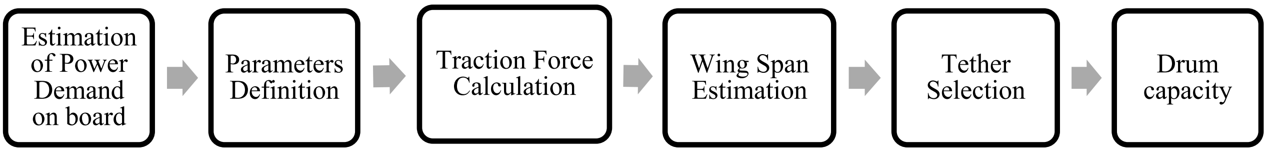
5. Discussion

This chapter contains the relevant discussions of the analysis of the models developed in the chapter 4. Thus, the discussion is divided in two parts; firstly, a debate about the scalability model; secondly, a consideration about the compatibility of the model. Note that the models are established in the concept definition phase.

5.1. Discussion of Scalability model

The scalability model has been developed in order to achieve a design able to provide 1.5 MW of power in contrast with the current prototype of 30Kw designed by Kitemill. This scaled-up model is needed to fulfill the power demand on board of the FSU Njord Bravo.

The scalability model is the following:



On the Step 1 the power demand has been estimated. Despite the energy balance on board the FSU Njord Bravo could not be provided by Aibel, the calculation was based on the current power supply installed on the vessel, which is 1.8 Mw, however, for safety measures, the power actually consumed is normally a 60-70 % of the power installed. It is an appropriate assumption when the power demand on board is defined to be a 65% of the 1.8 Mw provided. The result is 1222 Kw, so it is decided that the AWT on board should at least provide a power output of 1.5 MW.

On the Step 2, all parameters needed to scale- up the AWT are defined. All values are assumed to be the most used in the industry for design of kites or Airborne technology. These presumed parameters lead us to obtain more reliable results since they are based in current applications in the industry of Airborne Wind Turbines.

The estimation of the steps 3 and 4 are based on the simplify crosswind kite power researched by Lloyd [19]. The equations have been rearranged; it results several values of traction force and aerodynamic areas for different wind speeds.

On one hand, according to the Lloyd model, the traction force is function of the power output and load speed. The outputs show a decreasing traction force for higher load speed (1/3 of the wind speed). This is because the simplified model states that the increasing magnitude of the load velocity will cause a reduction of the traction force. Also, the power output is kept constant, but in reality, the power output should vary in terms of the traction force. So that, if the wind speed and traction force (lift for crosswind kite) are high, the power output shall increase. Nevertheless, the traction force which provide a power output of 1.5 MW when the wind is blowing at 12 m/s is 375 KN. This analysis suggest that the traction force equation for the power output proposed by Lloyd Miles [19] shall be reviewed and improved in details.

The design to be considered for the FSU Njord Bravo is supposed to be exposed to a 12 m/s wind speed. The reason that this was followed is because the data collected from Kitemill for the 30 KW prototype were given for this wind conditions only. However, it is a good design criterion for the scaled-up AWT, since it is known that the wind that blows at 500 m of altitude in the Nord Sea is from 10 m/s and above [8].

Similarly, the wing span have been estimated. The wing span have been based on the maximum theoretical value of aerodynamic efficiency, which in real application is not achieved. Nevertheless, for this AWT preliminary design phase, it is worth assuming a Power coefficient (Cp) of 4/27. The optimal wing span of the aircraft forming the AWT is 14 m for a power output of 1.5 MW, at 12 m/s. However, future CFD to check the lift-to- drag ratios of the airfoil should be performed. Moreover, a circular swept area has been assumed, as it is in the traditional HAWT, but in the airborne technology the flight mode is differently adjusted, basically drawing an infinity symbol. A test of the wing span estimated for the range of wind speeds presented shall be done in the future, so that, it shall be possible to note the aerodynamic efficiency and the power output of the actual design.

The steps 5 and 6 are directly related to the traction force estimation. In pursuance of calculating the tether diameter and the drum capacities, manufacturers of fiber ropes and trawling winches have been consulted. The most suitable tether diameter is 30 mm to withstand a traction force of at least 375 KN, whereas for the drum capacity the diameter of the drum is 1200 mm, since it was assumed per recommendation of Kitemill that it should be 40 times bigger than the tether diameter. This might differ with current manufactured trawling winches in terms of traction force and dimensions, yet it complies with the DNV-GL standards for loading gear on seagoing vessels.

Although, new winches designs should be looked into and be manufactured so that it may fulfill the technical specifications required for this scaled-up AWT.

5.2. Discussion of Compatibility model

The compatibility model has been developed with the intention of analyze how the scaled-up AWT could be fitted in the FSU Njord Bravo to provide electricity on board. The model is as follows:

On the first step, the dimensions and weight of every component that form the AWT have been calculated. The values have been computed through manufacturers consultancy or simple approximations, whereas for the second step the General Arrangement of the FSU Njord Bravo have been provided by Aibel. Consequently, used to estimate the rooms and decks dimensions. These two steps are discussed together in this section but shorted by components of the AWT.

Firstly, the generator has been calculated based on a similar rated power generator manufactured by *Stamford power generation*. The weight of this machinery is similar to the current diesel generator installed on board. As per the dimensions specified by the manufactured it is possible to fit it in the room of the vessel destined to accommodate engines and generators. Thus, the retrofit is compliant with the Rules and Regulations for electrical installations on board explained in chapter 2.

Secondly, the winch that wind in the tether is the heaviest component, it has to be attached to the generator, therefore both are allocated in the same room. The weight has been calculated with a simple approximation to the volume calculation of a steel cylinder. In this assumption, the weight of small components and flanges of the winch has not been considered, but it contributes at least a 5 % of the overall weight of the machinery. In terms of the dimensions, they were scaled up on the previous model, however, it has to be noted that the diameter of the winch should match with the diameter of the generator. In the case studied, there is a mismatch of 30 mm between these two components. A solution might be provided by winch manufacturers, so the tether and maximum capacity of the winch do not get compromised.

Overall, it is possible to install the winch together with the generator inside the auxiliary engine room. Nonetheless, the stability of the FSU must not be compromised at any time and a detailed study of it shall be perform

Thirdly, the weight of the tether has been computed. It has been based on the specifications of the tether estimated on the scalability model. The weight of the tether was calculated provided that its material is light polyethylene, the mass obtained per unit length is 0.62 Kg/m. Generally, the weight of the rope will not affect the overall mass of the AWES when it is installed in a very large vessel. Nevertheless, it was not considered in the scaled- up model. This high weight result definitely contributes to a high drag force on the tether and consequently will negatively affect the aerodynamic performance of the AWT, which may lead to crosswind power loss. Therefore, in the next phase of the designing process, a detailed tether model shall be computed.

Lastly, the aircraft the main component of Airborne wind Technology. The dimensions have been established with the scalability model. The wing span is defined to be 1.8 bigger than the 30Kw prototype, therefore the weight and the other relevant dimensions have been computed as 1.8 times bigger than the current development. It results in approximately 70-90 Kg. This range contains the minor components weight such as the propellers, sensors and battery pack that should be taken into account. In terms of deck availability, the aircraft and its take-off and landing platform must be fitted in open space and the uppermost decks on the FSU Njord Bravo. Nonetheless, the operational mode of the aircraft should not interrupt the normal operation conditions of any other system installed on board as cranes. The most critical operations that may interact with the AWT are the helideck operation, in case of emergency or crew change, and the mooring operation. In the model of this study it is assume that the flight mode of the kite is static and does not contribute to the propulsion or motions of the vessel. Although, the mooring turret together with the DP system are in operation such that the vessel remains in position under strong wind and sea states, the AWT will tend to propelled and move the vessel if the tractive force is enough to do so, consequently, further dynamic analysis with the operation of the AWT on board should be studied.

Finally, the step 3 of the compatibility model is discussed. The set-up is an innovative idea of how the new system as power plant may be retrofitted into the FSU Njord Bravo. Not only the location of the take-off and landing platform, but also the connecting pipe between the Auxiliary engine room and the aircraft.

The set- up proposed in this step requires structural changes in the vessel, which should be performed according to the resolution by IMO in Ship construction for Bulk carriers and Oil tankers.

On one hand, the connecting pipe contains the tether connecting the winch in the auxiliary room to the aircraft in the Poop deck; it implies that it has to go through deck plates. This design might affect to the loss of tractive force generated by the aircraft flying, which results in a smaller power output. Moreover, the length of tether needed is increased by the length and shape of the pipe itself. On the other hand, the take- off and landing platform involves a change in area of the Poop deck, such that it does not interrupt the operation of the upper deck crane nor the Heli deck. Thus, the aircraft operation will not be affected by any other equipment installed on the surroundings.

Overall, the models give basis to whether proceed with the next step of design or improve aspects of the vessel or AWT accordingly.

Chapter 6

6. Conclusions

This study aims to answer the question if the rigid wing Airborne wind technology in current development is scalable and compatible to provide electricity on board of a ship.

The answer is yes, the rigid wing airborne wind technology is scalable and compatible in size for the case scenario used, provided that the technology of Kitemill is in an early stage of development and the FSU Njord Bravo power demand is not as high as other ships in the industry.

Essentially, the model used for scalability is reliable and valid for a preliminary design phase of the airborne wind technology. Yet, it shall be reviewed for a detailed design phase. The model is based on several assumptions that carry limitations of the applicability of this concept in the maritime industry.

Overall, the increment in the size of the aircraft limits the aerodynamic efficiency of the AWT. The aerodynamic efficiency will be affected by the tether increased diameter, since it raises the drag force on the system. In the present model, the drag contribution of the tether in crosswind flight mode has been neglected. Moreover, the augment in the aerodynamic area may result in the need for applying different lift to drag ratios than the ones currently used in Airborne wind technology airfoil design. Consequently, if higher power outputs are required, CFD analysis of the technology with actual wind field data in Njord Field, Norway, shall be performed.

Additionally, the model developed for compatibility of the technology is also reliable and valid. The application of this model tells whether the application of the Airborne wind technology is compatible or not with the vessel it will be installed on. In the case study implemented in this research, the rigid wing airborne wind technology is compatible. However, the interaction with the operation of other systems on board shall be studied for safety analysis and vessel integrity, such as stability, vessel motions, marine operations as well as uncertainties related to air traffic and weather forecast.

To sum up, both models might be applied to any crosswind airborne wind turbine and any commercial vessel. Accomplishing that this research proposes the steps to be followed on the preliminary design phase of an AWES as electricity generation of a vessel.

To complete the research, it is important to mention the lessons learned with the study. The main teachings are:

- The traction force is the most critical design parameter of the AWT for scalability purposes. The equation of power output of the simplified crosswind model proposed for Lloyd Miles L [19]. Shall be reviewed and improved.

- There is a big complexity of merging Airborne wind technology and the ship technology, especially when it comes to the airborne turbine motions and the vessel motion in terms of relative wind speed. The simplified model shall be reviewed adjusting the relative wind speed with the vessel motions and environmental loads.

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