Routing Methods and Design Considerations for Autonomous Unmoored Floating Wind Turbine Concepts

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By

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Summary

This thesis project titled "Routing Methods and Design Considerations for Unmoored Floating Offshore Wind Turbine Concepts" investigates the emerging technological deployment of Unmoored Floating Offshore Wind Turbines (UFOWTs) which are operated via autonomous routing to navigate their constantly changing wind and generation sites. This form of wind energy conversion offers the opportunity for wind energy harnessing further offshore and in deeper water sites than currently possible along with theoretically shorter deployment times. These two advantages along with other identified for this technology aid the upcoming 2050 goals of the Net-Zero Coalition for renewable energy generation. The current prevailing research focus on UFOWT systems in literature is concept development and modelling to demonstrate pre-feasibility in terms of stability, costs, and energy balance. This thesis aims to evaluate two prevailing routing methods and system designs of UFOWT concepts and to investigate how operational method, design choices and site conditions interact with one another to affect the UFOWT performance.

The research workflow of this project can be divided into three processes. The first involved a literature review that provided the author with the necessary understanding of existing work in the realm of UFOWTs that provided guidance for the research question formulation. This first research process blended into the second which involved defining two separate UFOWT designs to investigate in this project, each with their individual routing method: Alternating Navigation and Generation (ANG) and Continuous Navigation and Generation (CNG) methods. The system modelling scope was defined in this step, setting assumptions for aspects that could not be covered in the scope of work. The third process involved building the simulation environment for the UFOWTs from the ground up, this was done in MATLAB (R2021a version) using weather data from the Copernicus ERA5 opensource database.

The results of this project were simulated routes and energy yields for operation of each UFOWT design in the North Sea, West and Eastern Mediterranean Sea regions. Using the same UFOWT design in all regions showed poor performance in lower average wind speed areas, due to lower generation and increased costs associated with further distances travelled and dictated by the routing algorithm. Over the period of 10 years for which data was available to simulate both systems, it was found that there are additional considerations to be made for UFOWT operation which influence overall performance, for instance starting location and wind speed direction trends. Operation of the two UFOWT designs was simulated in 3-month intervals from 2012 to 2021, which yielded an average performance of the ANG system nearly twice as high than the CNG system, in terms of capacity factor and simulated onboard fuel conversion.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
ADOWT	Autonomously Driven Offshore Wind Turbine
ANG	Alternating Navigation and Generation
CGH2	Compressed Gas Hydrogen
CNG	Continuous Navigation and Generation
DC	Direct Current
DPS	Dynamical Positioning System
EEZ	Exclusive Economic Zone
ES	Energy Ship
EY	Energy Yield
HAWT	Horizontal Axis Wind Turbine
LH2	Liquid Hydrogen
MOWES	Mobile Offshore Wind Energy System
MOWT	Mobile Offshore Wind Turbine
NZC	Net-Zero Coalition
PEM	Proton Exchange Membrane
PS	Power Ship
SOEC	Solid Oxide Electrolyzer Cell
TRL	Technological Readiness Level
UFOWT	Unmoored Floating Offshore Wind Turbine
UN	United Nations
VAWT	Vertical Axis Wind Turbine

Nomenclature

a	Induction factor	-
α	Current direction	rad
A_r	Wind turbine rotor area	m^2
A_w	Wetted surface area	m^2
C_D	Drag coefficient	-
C_f	Frictional coefficient	-
C_p	Power coefficient	-
C_{xc}	Current load coefficient	-
D	Turbine rotor diameter	m
d	Draught	m
η	Drivetrain efficiency	-
F	Forecast time	hr
F_w	Drag force	N
h	Starting hour	hr
$\dot{m}$	Mass flow rate	kg/sm^2
μ	Dynamic viscosity	Pas
M_{disp}	Displaced mass	kg
M_{TOT}	Total turbine system mass	kg
L	Characteristic length	m
P	Power	W or MW
R	Hull cross section radius	m
ρ_w	Water density	kg/m^3
ρ_a	Air density	kg/m^3
S	Stationary operational time	hr
T	Max travel time	hr
T	Thrust force	N
v	Kinematic viscosity	m^2/s
V_b	Travelling speed	km/hr or m/s
V_{barge}	Displaced volume	m^3
V_c	Current speed	m/s
V_d	Downstream wind velocity	m/s

V_i	Inlet velocity or cut-in speed	m/s
V_o	Outlet velocity	m/s
V_r	Wind velocity at the turbine rotor	m/s
V_{rated}	rated wind speed	m/s
V_u	Upstream wind velocity	m/s
V_v	Vessel velocity	m/s
W_h	Safe mean significant wave height	m
X_c	drag force	N
y	Year of data set or simulation	yr

1 Introduction

This thesis looks at an emerging and new method of deploying wind energy offshore, which side steps some of the current bottlenecks constricting wind energy deployed with fixed and moored foundations. *Unmoored Floating Offshore Wind Turbines* (UFOWT) are design concepts that have been proposed since approximately the 1930s, some of which have reached the prototype phase as turbines assisting ship propulsion while other concepts focusing on electricity generation continue to evolve as an emerging technology. In short, UFOWTs are altered floating wind turbine system designs adapted for navigation and on-board energy storage which are completely autonomous, can follow optimal wind conditions and potentially offer shorter permitting, deployment time and costs than conventional offshore wind energy technologies.

1.1 Thesis Aim

The aim of this thesis report is to investigate the interactions between proposed designs and proposed modes of operation for UFOWT systems commonly found in literature. The outcome of this project is meant to provide a starting point for further modelling of UFOWT systems in their long-term operation since it combines different research areas and disciplines to provide a pre-feasibility assessment.

The project begins with research in the current areas of focus for development of UFOWTs, which also highlights the current literature gap that this thesis project contributes to. Following this, two dominant routing methods used in literature and their respective system designs are picked and modelled in a MATLAB environment. The choice of UFOWT systems modelled in this thesis project follows the current trends in literature and draws on the current European wind industry trends when needed to prioritize the study on relevant system designs that would likely continue to be studied in further research. To test the routing algorithm and decision process, two site types are used to test and evaluate the design characteristics of both UFOWT systems and their routing method. By changing certain design variables and parameters used in the decision algorithm, an evaluation is done on how UFOWT technologies can be more effective in their operation depending on their design, site location and routing technique.

1.2 Research Questions

This thesis report focuses on investigating the following four research questions.

1. *How does the routing algorithm logic and decision process of a UFOWT system influence its operation and performance?*
2. *How do the system components and design choices of a UFOWT interact with its routing method?*
3. *How do different climatic and geographic conditions influence the operability of a UFOWT design and routing method?*
4. *What barriers and drivers play a role in the development of UFOWT concepts beyond their early research phase?*

The aim of the initial two questions is to investigate the effects of routing methods on design and vice versa, drawing conclusions on how these two aspects of UFOWT must be developed together if rather than apart. The third research question aims to investigate the role of site investigation in the realm of UFOWTs, to see how characteristics of different sites impacts requirements on UFOWT design and operation. The last research question tries to collect the learning that is made during the thesis project when coming across accelerators and barriers to this technology, to give a final recommendation on both further research continuing from this project but also other areas of interest that could be focused on or drawn upon for future research on UFOWT.

1.3 Structure

The following report is structured in 6 Chapters whose content is briefly summarized below:

- **Chapter 2: Background & Literature** explains the background to UFOWT concepts, including the driving factors that have led and could continue to develop this niche technology and the working principle of UFOWT.
- **Chapter 3: System Designs** specifically details the mechanical and electrical system along with the operational area choices for the study in this report including a rationale.
- **Chapter 4: Modelling & Methodology** explains the evolution of different working models.
- **Chapter 5: Results** shows results of the two UFOWT systems in two different site locations along with a direct comparison of these.
- **Chapter 6: Conclusions** aims to answer the research questions presented in this chapter and provide guidance for further research and development on this thesis topic.
- **Chapter 7: Further Research and Developments** presents a few points from which further research could continue from this thesis project based on the assumptions, limitations and related areas of research encountered during the project.

2 Background & Literature

The aim of this chapter is to provide a background on the history of wind energy and currently proposed concepts of UFOWTs in literature. Section 2.1 first dives into the offshore wind market to identify the key drivers and players for UFOWTs. Section 2.2 then explains what the technological category of UFOWTs consists of, how UFOWTs have evolved with time and what the role of other similar technologies has been in this evolution path. Section 2.3 dives deeper into specific UFOWT systems and their differences. Section 2.4 provides a theoretical explanation on the working principle of UFOWTs to demonstrate how they differ from regular moored floating or fixed foundation wind turbines. To conclude this Chapter, Section 2.5 draws a summary of the literature work on UFOWT by detailing the scope of work and systems investigated by certain authors which were drawn upon most in this thesis project and aided the formulation of the research questions.

2.1 Wind Energy Industry

In the global effort to move towards electrification and renewable energy generation, wind energy plays an important role to balance other renewable sources such as solar, hydrokinetic, ocean, geothermal and biomass energy [1]. Under the United Nations (UN) Net-Zero Coalition (NZC) by 2050 ninety percent of global electricity will need to come from renewable energy sources, where wind and solar energy should account for approximately seventy percent of this [2]. In 2022 the global installed capacity of wind energy was 837GW [3] but under the net zero scenario this will need to expand to 3106GW by 2050 [3], this will require reductions in permitting, siting, and project development time along with project costs. In the 136 years since the first conversion of wind to electricity, wind turbine concepts have evolved to strive for cost competitiveness with other energy generation technologies.

2.1.1 Historical Development

Wind energy electricity conversion was first demonstrated with the first Horizontal Axis Wind Turbine (HAWT) used for electricity production onshore in 1887 [4]. It took nearly 100 years to see the first onshore wind farm in 1980 [5] which was quickly followed by the first offshore wind farm in 1991 [6]. Since then, offshore wind energy has lagged in installed capacity, standing at 63.2GW in 2022 (approximately eight percent of the total wind energy capacity installed) [7], but contributed 22% of the 2021 94GW of added capacity. In the upcoming years the development of offshore wind will open possibilities for deeper water sites and installations farther from shore, aided by the introduction of floating offshore wind turbine foundations to the market since the first floating wind farm project demonstration in 2017 [8].

The innovation hub for offshore wind in the past years has been the North Sea which to date in 2023 has 30GW of installed capacity [9] and ambitions set by the European Commission to expand to 300GW by 2050 [10]. An important driving factor of this expansion is the soil type and water depth of the North Sea, it's continental shelf seabed has allowed for the maturing of the monopile foundation technology as it's a simple and effective solution for water depths up to approximately 50-60m [11]. The challenge faced today is the expansion of the offshore wind turbine technology to other regions which may have water depths beyond the feasibility of monopiles or jackets or simply that have unfavorable soil conditions for installation of these.

2.1.2 Floating Wind Energy

Due to the water depth limitations, increasing cost with turbine capacity and water depth of the jacket and monopile foundations, the floating foundation has emerged as a solution for sites unsimilar to the shallow North Sea waters (such as many areas in western and southern Europe with promising wind conditions). The use of mooring lines allows for deeper water sites and farther distances from the coast to be reached, rending it a suitable solution for water depths between 50 and 1000 meters [12]. Combination with on-site conversion of electricity to fuel to create autonomous systems has also emerged as a new offshore wind technology which would allow for floating wind turbines to push the distance from coast and water depth limits even further, since cable costs associated with grid connection still would limit the distance from shore. Hybrid wind systems such as these ones have not yet entered the demonstration phase as of mid-2023 [13] but are an ambition by multiple companies and governments such as the UK and Vattenfall to see the project 'Hydrogen Turbine 1' come to life in early 2025 [14]. Offshore wind energy still faces bottlenecks, both floating and fixed foundations for example the time that it takes both project types to be approved, manufactured, and deployed is far from what is needed for the upcoming 2030 and 2050 targets.

These project bottlenecks are exactly what UFOWT concepts aim to tackle. UFOWT provide most of the advantages of floating wind in terms of siting while also potentially side-stepping some of the permitting and time delays that are associated with the deployment of the final project. Although this technology presents its own new challenges and drawbacks, like any other emerging technology, research and development can bring it out of this pre-development phase.

2.2 Background on UFOWTs

This section dives deeper into the history that precedes modern UFOWT concepts, with the aim of providing a sociotechnical explanation of what has driven this technology thus far and what may continue to drive it in the future. Subsection 2.2.1 first presents the different technological categories that overlap and are relevant for the understanding and development of UFOWT. Following this, Subsection 2.2.2 presents the history of UFOWT systems along with Subsection 2.2.3 which briefly discusses energy ships as a relevant related category of technology concepts.

2.2.1 Technology Categories

First and foremost, it's necessary to properly define the category of *Unmoored Floating Offshore Wind Turbines* (UFOWTs), a term commonly used in literature [15]. UFOWTs fall in the technological category of Mobile Offshore Wind Energy Systems (MOWESs) or Mobile Offshore Wind Turbines (MOWTs), which creates the distinction between conventional floating offshore wind turbines and unmoored concepts. Other than UFOWTs, Energy Ships (ESs) or Power Ships (PSs) are included in the category of MOWESs, as they are vessels meant for energy generation with power plants on board and usually have an ulterior function related to transport. As there are many different types of ESs which also include non-renewable power plants, ESs referred to in this thesis are those with wind energy generation installed onboard. Within the category of UFOWT there is a distinction between Autonomously Driven Offshore Wind Turbines (ADOWTs), a term used by some authors to refer specifically to systems designed to constantly navigate during energy production [16], and floating wind turbines using Dynamic Positioning System (DPS) which instead are designed to stay in place during electricity conversion. This breakdown of technological categories is displayed in Figure 1 below.

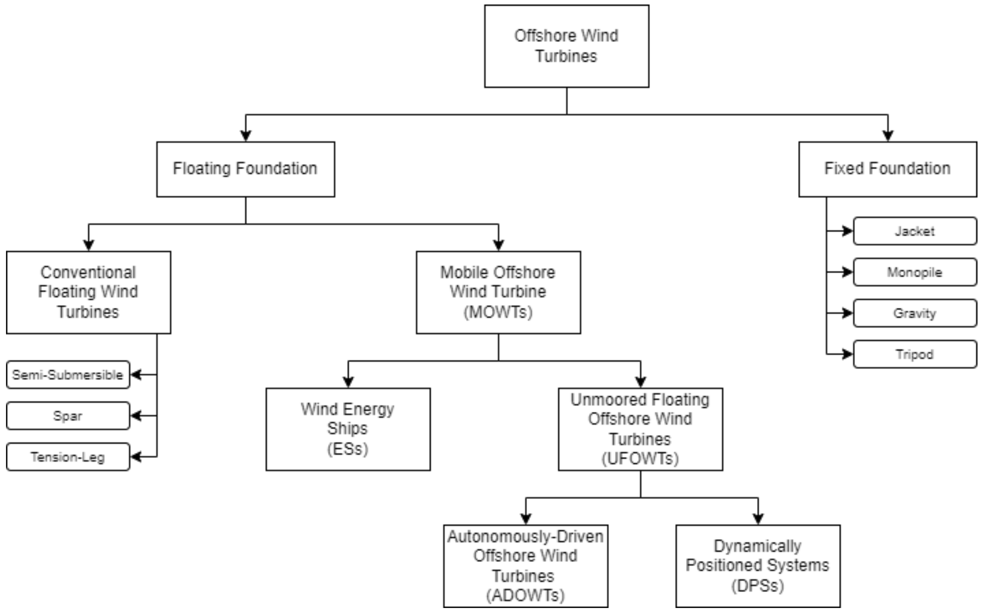

Figure 1: Technological categories of offshore wind turbines

As seen in Figure 1, UFOWTs are considered a branch-off from the floating foundation technological category that has been recently emerging in research and proof-of-concept projects. For this reason, their technological progress is correlated with that of floating wind energy in some respects.

A technological category not mentioned above but still relevant to the development of UFOWTs is the one for systems like ADOWTs that instead adopt hydrokinetic turbines for energy conversion, and a sail for navigation [17, 18]. These systems are often tied to UFOWT research for the similar auxiliary components and operation that a UFOWT system may have as well. Beyond the system design, the routing and operational method is also of interest since these autonomous systems need to sail changing wind conditions and make routing decisions to maximize their energy harvesting.

2.2.2 History of MOWTs

The history of MOWTs is relevant when it comes to identifying the driving factors that pushed for research and interest in these systems. Having these well identified, gives a clearer idea of how this technology could emerge in the wind energy market and which stakeholders and technology drivers may be used as an advantage or may act as barriers. What is interestingly evident when researching MOWT systems is the pattern in which research is published in literature. Figure 2 below shows the distribution of MOWT concept research publications that were reviewed and identified as relevant to this thesis project, this does not include all research on MOWT but mainly the most cited sources that were found across different global research groups, these are included in Appendix A. Keywords used to trace part of these articles included “UFOWT”, “MOWT”, “MOWES”, “Unmoored”, “Energy + Ship”, “Autonomous + Wind”, while many were directly found by referring to the references already found articles.

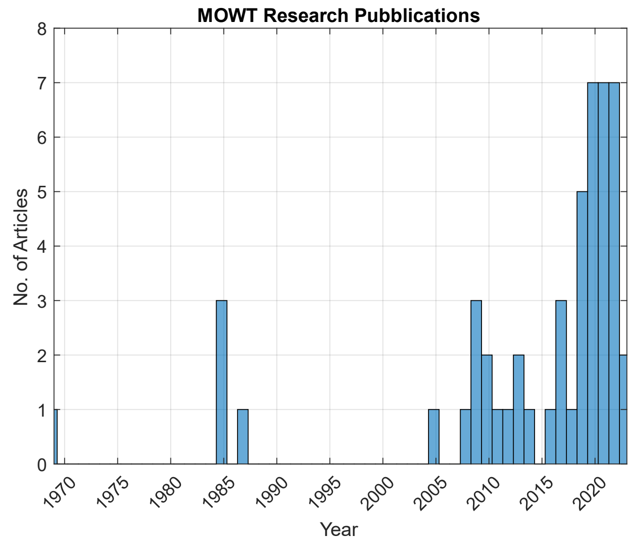

Figure 2: MOWT research publications over the years 1969-2023

Although it's evident that MOWTs, especially UFOWTs, are more of a novel concept emerging in the recent years, in the past it's noticeable that interest in MOWTs may have been pushed by energy crises of 1970-1980 and 2008. The first ES systems were proposed early as 1870 [19] which later evolved to proposals of vessel installations of wind turbines mechanically coupled with propellers leading the way for the evolution of Energy Ship concepts. The research in the 1980s focused on the integration of wind energy conversion and navigation, on research such as the optimal blade design for windmill boats and theory investigations into windmill thrusters [20, 21]. More recently with the emergence of floating wind energy as a concept, UFOWTs have risen in popularity as research has focused more on development of floater designs and the entire floating wind turbine concept has been proven through project executions.

In the past three years research on UFOWT systems specifically has been picking up globally, the involved research groups and parties work within and outside of Europe. For example, the Ecole Centrale de Nantes in France [17, 22, 23, 24, 25], University of the Basque Country in Spain [26], University of Bremen [27] and Stuttgart [28] in Germany, in Finland at the University of Helsinki [29], at the Technical University of Denmark [16], and beyond Europe in China at Shanghai Jiao Tong University [30], University of Massachusetts in the USA [31], and The University of Victoria in Canada [32, 15]. The source of this UFOWT specific research in research groups that are not already focusing on this area comes likely due to each of these sources' origin from wind energy focused research groups.

2.2.3 Energy Ships and their Relevance

Energy ships offer a fuel saving solution for offshore operations, specifically the transportation sector. Some research proposes use of route optimization with energy ships to improve the energy saving even more [24] which offers the possibility of reaching even higher capacity factors for the energy ship system. Energy ships operation has been simulated and shown to produce higher capacity factors than fixed site wind turbines under certain conditions [33], which supports the proposed concept of a moving wind turbine. The technology of ES specifically using wind as a power source are closer to their proof-of-concept phase than UFOWTs are, as there are already built and operational ships using wind rotors such as Flettner rotors to convert wind power to electricity [34].

The overlapping areas of interest for ES concepts and UFOWTs is the mode of operation. Since the principle of ES involves the combination of wind energy production with another existing function, the designs for the foundation and auxiliary components are meant to support more than what an UFOWT concept would require in terms of stability, navigation, and storage. In terms of design ESs cannot provide much of a proof of concept of UFOWTs since they usually implemented in a larger capacity scale on already larger scale vessel foundations than the currently proposed UFOWT concepts in literature. On the other hand, the operational method and routing of ES is very similar to that of UFOWTs, since one of the functions is to alter navigation to seek out specific wind conditions. Demonstrations of improved capacity factors in response to routing algorithm development is a knowledge area that can instead be directly transplanted into UFOWT concepts. So far in the proposed studies and simulations energy ships implementing wind energy show capacity factors equivalent or higher than fixed wind turbines located in the same areas [33, 23].

2.3 UFOWT Designs

There is extensive variety of UFOWT designs investigated in literature since it is still an emerging technology. The designs can be distinguished by a few categories; foundation type, turbine type, deployment size, energy conversion or storage method and routing methods. This section looks at each of these categories to present the trends in literature and provide a background to how designs are selected for investigation in Chapter 3.

2.3.1 Foundation Types

One of the largest varieties in designs involves the foundation of UFOWTs which range between use of vessel-type ones, barges or semi-submersible structures used currently in floating wind or even spar-buoy foundations. The variety of foundations is justified by the lack of a proven concept for UFOWTs, the still present variety of foundations proposed and used for floating wind projects and a variety of technical requirements for the foundations in different proposed UFOWT designs depending on the application and scale of the investigated concept. An illustration of the differences between designs found in literature in terms of foundation types is seen in Figure 3, Figure 4 and Figure 5 below.

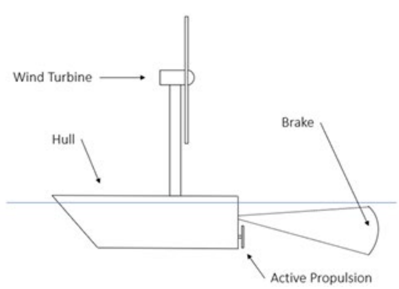

Figure 3: Vessel type foundation with propeller and water brake system proposed by Rickert [27]

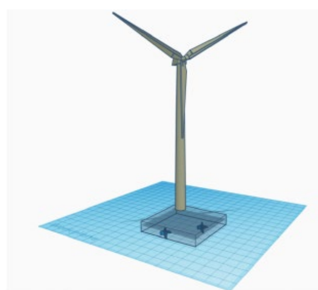

Figure 4: Barge type foundation with dual propeller DPS proposed by Alwan [25]

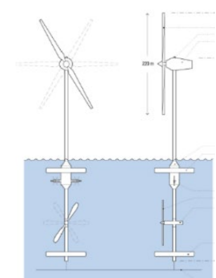

Figure 5: Spar-buoy type foundation proposed by Raisanen [29]

Vessel-type foundations (that range between catamarans, cargo ships, ferry) are proposed in combination with horizontal or vertical axis wind turbine systems, depending on the capacity of the turbine and application [31, 16, 35, 36, 27, 37]. Here there is an overlap between the research areas of ES and UFOWTs, since all ES concepts employ vessel type foundations and are designed to continuously move during electricity generation. The capacity ranges of the turbines investigated in literature with vessel type foundations go from 0.005MW [35] to 0.6MW [36] to 1MW [36], 3MW [25] and 5MW [16]. Other relevant literature works using vessel-type foundations are those employing hydrokinetic turbines, which use catamarans [22].

Barge and semi-submersible foundations are proposed by many looking at systems whose function is only to produce and convert electricity [38, 32, 17, 30]. A similarity with all these systems is that they are meant to stay fixed in place during production, they use a DPS to do so. Likely due to the greater stability offered by a barge/semi-submersible foundation, larger turbines are investigated in the studies using these foundations, such as 1MW [25], 2MW [38], 5MW [30], 15MW [32]. These types of foundations are also taken or could be adapted to reflect existing and proven foundation designs in the floating wind energy industry.

Spar-buoy type foundations instead are the less common designs proposed in literature likely due to their lower stability for use without mooring lines [29, 39]. For use of these types of foundations with UFOWT designs, it's recommended that they be altered to have a lower center of gravity to improve the stability issue [29], although this may have consequences on the ability of the system to autonomously navigate.

2.3.2 Turbine Types

Amongst the studies both Horizontal Axis Wind Turbines (HAWT) [31, 38, 16, 35] and Vertical Axis Wind Turbines (VAWT) [17] were proposed. For the VAWT systems, most used a Flettner rotor, and these were most popular especially amongst the ES systems which employed more than one VAWT onboard a single vessel [17, 24, 34] . The main advantage highlighted in literature for use of a VAWT system for both ES and UFOWTs is the fact that wind in any direction can produce electricity with no yawing requirements. Meanwhile, conventional HAWT wind turbines require yawing and proper alignment with incoming wind, but they also provide a simpler stability problem for floating systems compared to the vertical axis alternative since there aren’t the same centrifugal stresses involved [36]. Examples of systems investigated in literature for both conventional 3-bladed HAWT and Flettner rotor VAWT are shown in Figure 6 and Figure 7.

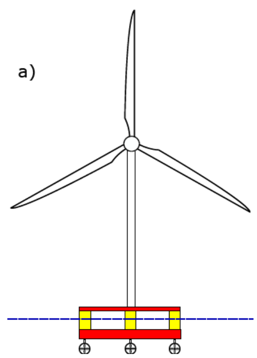

Figure 6: HAWT concept investigated by Connolly & Crawford [15]

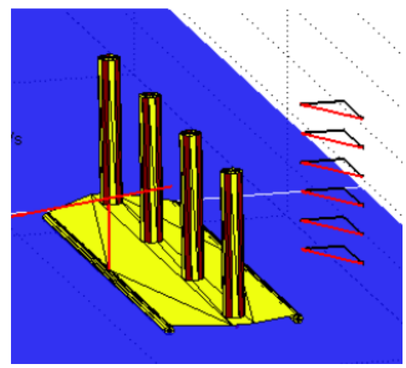

Figure 7: VAWT concept investigated by Gilloteaux [17]

As discussed in the previous subsection, a wide range of turbine ratings is investigated in literature. For practicality, the placement of a readily available wind turbine on a separate foundation is done to simplify modelling and represent what would likely occur for the fastest assembly of a UFOWT system. For this reason, much of the literature uses the widely used market wind turbines, especially for the HAWT systems which can refer to the widely used and distributed 3 bladed design used predominantly on fixed foundations.

2.3.3 Single vs Farm Deployment

There is a difference in literature also amongst single wind turbine and farm proposals and research. Some literature works identify and focus on the potential of UFOWT systems to be deployed as a farm rather than single turbine systems [40, 29]. In the farm deployment there is still the distinction between a farm which uses DPS [29] and one that sails with the wind [40]. Some potential advantages of a UFOWT farm over a conventional moored or fixed foundation farm is the possibility to rearrange the sailing formation to reduce wake losses, to improve the efficiency of sea space used (since UFOWTs require less spacing between each turbine due to lack of mooring lines), and possibility of transport of onboard produced fuel directly to the collection points with no need of intermediary vessels [30]. Two examples of farm concepts proposed in literature are shown in Figure 8 and Figure 9.

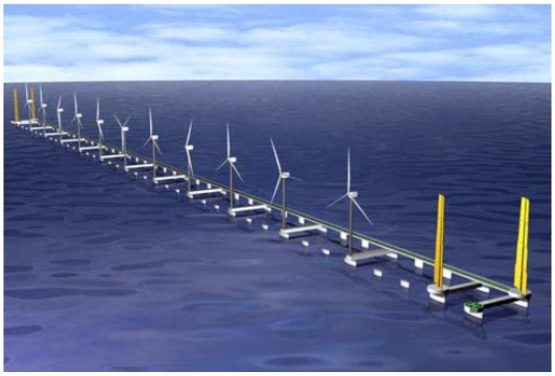

Figure 8: Connected horizontal axis UFOWT farm array proposed for operation in the Japanese sea [40]

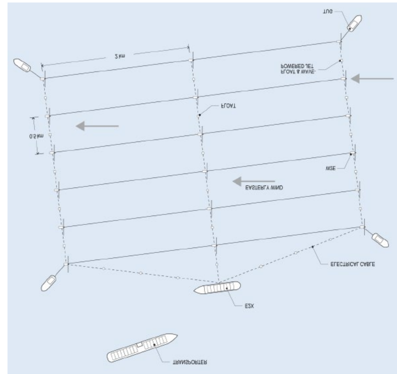

Figure 9: Open-ocean wind farm concept proposed for production of different fuel types [29]

The operation of these farm concepts differs dramatically, where the array of wind turbines in Figure 8 is made to navigate the seas, much like the ADOWT concepts previously described while the farm concept in Figure 9 is designed to be kept in place during operation while only allowing rotational movements to best align the farm with the incoming wind. Other farm concepts that are proposed are those involving many individual ADOWTs which sail and convert electricity to fuel independently while communicating between one another for routing decisions. A notable advantage of the farm proposals in the figures above compared to this latter farm concept is that the turbine units can be connected electrically with cables to few fuel conversion and storage units (ultimately reducing losses and system costs). The lack of mooring lines also has the advantage of allowing for more densely packed farms since there is not the same distancing requirements [30].

2.3.4 Energy Conversion and Storage

Given the unmoored nature of all UFOWT concepts, there is an ever-present focus and research on the energy conversion onboard UFOWT systems. Many recent literature papers investigate hydrogen conversion due to its increasing relevance in global markets along with the advantageous high gravimetric energy density [24]. Currently Alkaline and Proton Exchange Membrane (PEM) electrolysis are the commercially available technologies, and both are at the same level of technology readiness (TR9). Alternatively there are the options of Solid Oxide Electrolysis (SOEC) and Anion Exchange Membrane (AEM) electrolyzers, where SOEC lead the way in its demonstration phase at the multi-MW scale and technological readiness level (TRL) of 8 [41].

The storage method of hydrogen instead varies quite a bit across literature research given the still developing and expanding nature of this technology different methods are still developing in scale to become more cost competitive. Some of the options involve liquid hydrogen (LH2), compressed hydrogen (CGH2). Between liquid and compressed hydrogen, the driving factors are the higher efficiency of the CGH2 method and the lower long-term cost of the LH2 solution [24]. Other storage possibilities include conversion to Methanol (CH3OH) or Ammonia (NH3) through Haber process.

Other storage methods include batteries or forms of mechanical storage through compressed air or water pumping. These each have very different volumetric and gravimetric storage capacities than hydrogen conversion and storage and have been investigated for pairing with wind energy [42]. Specifically with use of UFOWT systems, there is a limitation on space and weight of the storage method since this needs to not only be placed on a floating structure that needs to support the weight, but also one with the function of navigation.

2.3.5 Routing Methods

The routing method is an essential part of the UFOWT system, as it determines the site in which the system operates and so the capacity factor. Based on the method used, the same physical system can yield different performances. Two general categories of routing methods were identified in literature, the first was the method of fixed operation while the second involved moving operation.

Fixed Operation

The first type of routing method is one employed by systems using DPS or other forms of braking to keep the system temporarily stationary. These systems are designed to stay in place and maintain stability by using DPS and producing electricity in an approximately fixed area. The reason for employing DPS rather than mooring lines can range from lower cost, faster deployment of these systems and possibility to move this system to a better wind location after deployment. In literature these systems are mostly described and investigated from a stability, and energy balance perspective to investigate the specific effect of replacement of mooring lines with DPS. Even though the replacement incurs an increased energy cost, analyses thus far still show that it is a feasible arrangement since the “power ratio” measuring the ratio between produced and expended power is greater than one [30].

Within the range of applications of fixed operation systems, there are some that indeed operate like a conventional wind turbine/farm staying in one general site area, while others open the possibility of moving the turbine to different sites based on the changing wind conditions. The first operational method involves an assessment and forecasting of future wind conditions and directions, to decide on the orientation of the system and/or farm. The second system type meanwhile needs to construct a routing decision based on current energy storage conditions and future weather forecasts so that the system can feasibly move from one site to another while keeping an overall net positive energy yield.

Moving Operation

The first consideration to be made for moving systems is that when moving downwind, the perceived wind speed by the wind turbine never reaches the actual wind speed in magnitude [31]. This requires the turbine power curve to be adapted since higher actual wind speeds will produce less power in practice. Using a moving routing algorithm was found by some studies only beneficial in terms of outperforming fixed location wind turbines when the system was allowed to move far offshore. A study comparing the performance of fixed foundation and MOWT showed that operation far offshore yielded a capacity factor 10% higher [31], but this was only possible if the system was allowed to move and operate far offshore where wind speeds were on average higher.

Within the range of moving operation methods, there are different “sailing” strategies proposed and investigated. The simplest would be the downwind strategy which would likely not require any design alteration on the wind turbine used in the system, since the main difference of a system following the wind with constant alignment downwind would simply be the experienced wind speed which is lower than the actual wind. Other strategies include “crosswind”, “circular trajectories”, “beam reach” [27] and require for routing limitations to be placed to consider the stability limits of the system, along with considerations on operational area reach. For instance the downwind strategy is described in literature by some as a downwind/upwind combination, where energy is expended to move upwind after the system has been moved to a certain limit of the operational area by the downwind trajectory.

2.4 Working Principle of MOWTs

This section explains the working theory of MOWTs, firstly by summarizing the operation of a fixed wind turbine and identifying the changing conditions and effects of these for wind turbines that operate while the foundation is moving.

2.4.1 Classical Actuator Disk Theory

The basic principle of a wind turbine is explained using the actuator disk theory, aided by the graphic in Figure 10 below, and assumes inviscid and irrotational flow. This theory will be referred to as “classical” actuator disk theory since it uses a disk that is fixed in space, so that the frame of reference from the disk’s point of view and an observer fixed in space’s point of view are the same.

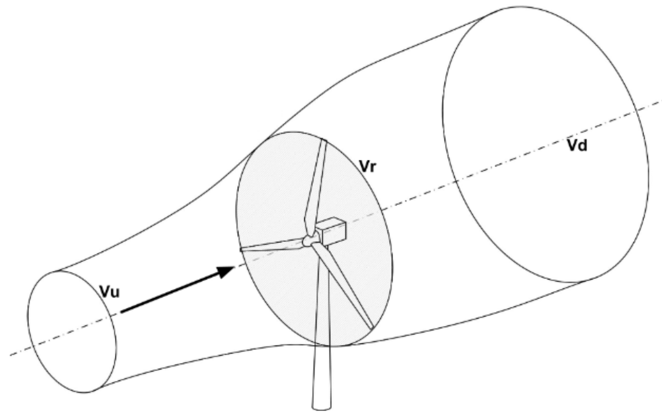

Figure 10: Actuator disk theory visualized with a wind turbine [43]

Using the stream tube as a control volume, conservation of mass dictates that the air mass flow in (or upstream to the turbine) must be equal to the mass flow out (or downstream to the turbine), while conservation of energy dictates that the energy of the incoming flow must be equal to the sum of the extracted energy from the flow and the outgoing flow. Due to the thrust force applied by the disk or turbine on the flow, some kinetic energy is extracted, slowing down the flow and creating an expanded stream tube as seen in Figure 10. The changes in flow velocity, V, mass flow rate, $\dot{m}$, momentum and energy are summarized in Table 1 below, where V_u is referencing the incoming or "upstream" wind velocity, V_r is the wind velocity at the rotor (or actuator disk) and V_d is the "downstream" wind velocity.

Table 1: Flow properties through a stream tube with a rotor or actuator disk at its center [42]

	Upstream	*Rotor*	*Downstream*
Velocity	V_u	V_r	V_d
Mass Flow	$\dot{m}$	$\dot{m}$	$\dot{m}$
Momentum	$\dot{m}V_u$	$\dot{m}V_r$	$\dot{m}V_d$
Energy	$\frac{1}{2}\dot{m}V_u^2$	$\frac{1}{2}\dot{m}(V_u^2 - V_d^2)$	$\frac{1}{2}\dot{m}V_d^2$

From the conservation laws, the power extracted, P, is defined as the work that the actuator disk or turbine applies on the flow while applying thrust force, T, which in turn is quantified by the change in flow momentum it creates. This is summarized by equations (1). The power extracted is also described by equation (2) which describes the energy of the flow at the rotor.

$$P = TV_r = \dot{m}(V_u - V_d)V_r \tag{1}$$

$$P = \frac{1}{2}\dot{m}(V_u - V_d)(V_u + V_d) \tag{2}$$

Replacing the relationship between the upstream and downstream flow defined by the induction factor shown in equation (3), the mass flow rate, thrust force applied and power extracted at the rotor are summarized in equations (4), (5) and (6).

$$a = \frac{(V_u - V_r)}{V_u} = \frac{1}{2}\frac{V_u - V_d}{V_u} \tag{3}$$

$$\dot{m} = \rho V_r A_r (1 - a) \tag{4}$$

Where A_r is the rotor area, calculated for a given diameter of the wind turbine and ρ or ρ_a is the density of air, or equivalent fluid used in this actuator disk theory.

$$T = \dot{m}(V_u - V_d) = \frac{1}{2}\rho V_u^2 A_r 4a(1 - a) \tag{5}$$

$$P = \dot{m}(V_u - V_d)V_r = \frac{1}{2}\rho V_u^3 A_r 4a(1 - a)^2 \tag{6}$$

This model is used to approximate the power extraction of a conventional fixed foundation or moored floating turbine. The theory is also applicable to UFOWT concepts that use dynamic positioning systems since their operation simulates a temporarily fixed wind turbine. For the case of ADOWT, operation and energy conversion occur during navigation, so the theory behind the derivation of the final extracted power formula differs slightly given that the actuator disk in the theory has its own velocity while moving through the air.

2.4.2 Moving Actuator Disk Theory

Although continuity, conservation of momentum and energy still hold, a moving actuator disk changes the amount of power extracted from a flow. Figure 11 below shows a sketch of a stream tube over a turbine moving to the right in the same direction as the wind flow, the upper figure section shows the frame of reference of the turbine while the lower figure shows the frame of reference of an external observer fixed in space. From the wind turbine's perspective, the experienced wind speed reaching the rotor is the difference between the freestream wind velocity, V_w, and the speed at which the wind turbine is moving, V_v, the vehicle velocity.

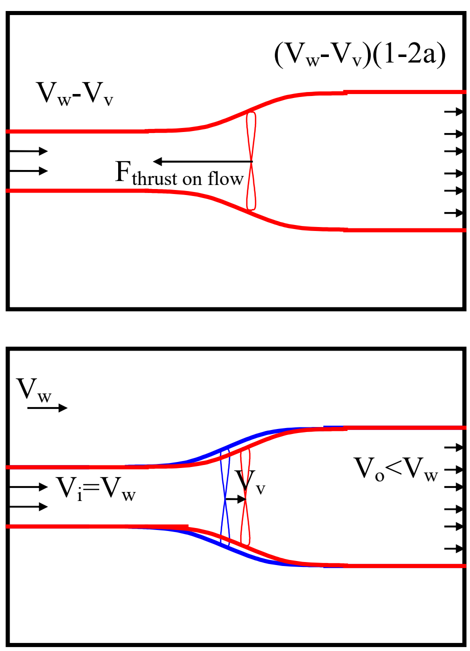

Figure 11: Stream tube sketches for frames of reference which are vehicle-bound (above) and earthbound (below) [43]

The figure uses V_i to refer to the stream tube inlet velocity and V_o to refer to the outlet velocity The movement of the actuator disk in the stream tube effectively reduces the available wind power that can be extracted from the same incoming wind stream, as described in equation (7) which can be converted to equation (8) by replacing the relationship of the axial induction factor.

$$P_{available} = \dot{m}(V_w - V_d)V_r = (V_w - V_d)(V_w - V_v)V_w\, \rho_a A_r (1-a)^2 \quad (7)$$

$$P_{available} = \frac{1}{2}\rho_a A_i (V_i - V_v)(V_i^2 - V_o^2) \quad (8)$$

Using the same theory by which the conventional actuator disk model derives the thrust and power exerted on and extracted from the wind, the equations for thrust (9), power (10), and drag (11) can be derived and are summarized below [27].

$$T = \frac{1}{2}\rho_a |V_v - V_w|(V_v - V_w)A_r 4a(1-a)^2 \quad (9)$$

$$P = \frac{1}{2}\rho_a |V_w - V_v|^3 A_r 4a(1-a)^2 \quad (10)$$

$$P_D = \frac{1}{2}\rho_a c_D |V_v - V_w|(V_v - V_w)V_v A_w \quad (11)$$

Comparing these to the equations (5) and (6) which gave the thrust and power for a fixed position turbine, the evident difference is the use of relative wind speed rather than the actual wind speed. For this reason, the power extracted and thrust applied by a moving wind turbine/actuator disk will always be inferior to a fixed one [31]. Another limitation is of course that for energy to be extracted, the difference between the vehicle velocity and the incoming wind speed needs to be greater than the cut-in velocity of the wind turbine. The theory presented for a moving wind turbine is applicable to UFOWT systems that navigate and produce energy simultaneously [27], although most theory presented in literature on these systems assumes that the wind and system trajectory are well aligned, and the system is moving downwind.

2.5 Existing & Recent Research

This section summarizes some of the most relevant and closely related literature research works that led to the identification and narrowing of the research questions presented in Section 1.2. Given the large variety of UFOWT systems studied along with the variety in scope of work of each research project, the following aspects were compiled and considered while conducting the literature review.

1. UFOWT system
    a. Wind turbine: type, capacity, modifications…
    b. Foundation
    c. Storage method
    d. Routing method
2. Methodology
    a. Operational site investigated
    b. Weather data used
    c. Forecast method
3. Results
    a. Parameters used to quantify performance

b. Method used to compare performance to fixed foundation

The system design used in each research article aided the selection of the UFOWT systems to be studied in this research project. It is expected that as the UFOWT technology evolves, proposed designs will narrow down to fewer and more frequently studied ones. The same can be said for the routing method which was mentioned in works only looking at long-term operation of UFOWT systems. For these specific types of research articles, the methodology with which the simulations were set up were noted, in order to grasp a better understanding of their limitations and areas of improvement that could be addressed by this thesis project. Additionally, the methodology of result collection and presentation was studied to determine how UFOWT systems are assessed in literature and how they can representatively be compared to fixed foundation offshore turbines. The table below showcases some of the most closely related research works to this thesis project, in terms of UFOWT design, routing methods and project focus.

Table 2: First authors and their research fields relating to UFOWT that aided the formulation of the following chapter 3 and formulation of research questions

First Author	*Year*	*Research Field*	*Involved Parties*	*Supporters / Funds*	*System Description*
Connolly	2022	Comparison of UFOWT and ES performance	University of Victoria Pacific Institute for Climate Solutions	Pacific Institute for Climate Solutions	15MW HAWT mounted on a semi-submersible foundation using 3 propellers for DPS
Xu	2021	Design of DPS controlled UFOWT	Shanghai Jiao Tong University Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE) Yokohama National University	National Natural Science Foundation of China Shanghai Sailing Program	5MW HAWT with semi-submersible, DPS system, chosen since it is most convenient for azimuth thrusters at the bottom of each leg for DPS
Alwan	2021	Investigation of DPS UFOWT concept	University of Adelaide Innosea LHEEA Lab Ecole Centrale de Nantes	WEAMEC (EOLNAV project) Region Pays de la Loire.	2MW HAWT Deployed in North Atlantic Ocean
Beseler	2020	Pre-feasibility analysis of ADOWT system	Technical University of Denmark	-	5MW HAWT on a catamaran foundation, alternating navigation and generation during routing
Annan	2020	Preliminary design considerations of UFOWT system	University of Massachusetts Amherst	-	10MW HAWT mounted on a hull foundation
Tsujimoto	2009	Optimum routing of UFOWT farm concept	Minami National Maritime Research Institute National Institute for Environmental Studies University of Tokyo Osaka University Hiroshima University Akishima Laboratories The Floating Structures Association of Japan	Technical University Berlin	5MW HAWT array on vessel foundation employing a type of continuously navigating and generating algorithm

Considering the recently contributing research groups, the LHEEA department of Central Nantes has been working on sailing wind turbine concepts since 2016 and beyond the research papers mentioned above also has developed a numerical model for a DPS UFOWT system of 2MW power rating named the EOLNAV project [46].This project and further research in the LHEEA lab is funded by the French region Pays de la Loire which is heavily involved in the development of its offshore wind energy industry [47] which currently hosts one third of France's installed offshore wind energy. Such an example of regional government involvement in research aids the fast development of technology at this early stage. Comparatively, the other research works have supporters and funds that are more on the national level or with smaller organizations/companies.

3 System Designs

This Chapter presents the research and decision process that followed the literature review phase and preceded the modelling phase. This involved choosing a limited few UFOWT designs to model, pick the specific system components, and choose the operational modes. Beyond the system designs, the operational area was also selected based on the research and considerations for UFOWT operation brought forward in literature. The outcome of this work phase is two detailed UFOWT systems each with their own operating method, each to be modelled in the North Sea and in the Mediterranean Sea in the following Chapter 4.

This Chapter begins with Section 3.1 which explains the rationale behind how this thesis draws from literature and industry design requirements to pick two different types of UFOWT designs. Following this, Section 3.2 describes the selection process for the operational area and discusses some factors that are both included and not included in this project as defining aspects of where a UFOWT system may operate. Section 3.3 then describes the system components that compromise each of the two selected UFOWT designs, including the rationale and method behind the choice of modelling. Section 3.4 then looks at the specific routing methods for each system and formulates guidelines for modelling discussed in the next Chapter.

3.1 Criteria for Design

Given the current vast variety of proposed MOWES designs and technologies in literature, it was necessary to arbitrarily pick two single UFOWT design for this thesis study. Choosing the design required the election of criteria to justify the design choice of one concept over the other, these criteria are outlined below. Revisiting the objective of the thesis which is to investigate the interaction between physical design and operational method of UFOWTs, the performance of these systems is used to evaluate this. This includes energy yield, autonomy, resilience to changing conditions and other resultants of long-term operation.

3.1.1 Proposed Concepts in Literature

This first criterion requires for the literature proposed designs and their recent trends to be evaluated when picking a design. Although UFOWTs as discussed are concepts that began appearing more than a century ago, it's more relevant to consider the recent research and work which highlights the academic interest in specific designs. The inclusion of this criterion allows for the thesis scope to remain on track and contribute to the literature assessment of UFOWT feasibility. The frequency of studies on specific designs shall act as a leading indicator of which systems should be focused on while considering the reasons brought forward for using the specific UFOWT design in that study.

3.1.2 Industry Trends and Technology Readiness

The second criterion involves the consideration of the direction in which the wind industry is currently moving and what types of systems and components are readily available to be implemented for UFOWT. Proposing and studying a design that would be technically feasible to construct with current technologies would rend the feasibility evaluation more realistic as well, given that the same production and installation methods of conventional wind turbine systems could be used. Given the expected relatively higher costs involved in research, deployment, and development of the auxiliary support components in UFOWT designs, components that do not necessarily need to be customized to the UFOWT design should be selected at their most widely used and low-cost. This also strengthens the credibility of the study by assuming the use of historically proven reliable components that would not need to be proven on their own before their use with a UFOWT system.

3.1.3 Safety and Autonomy

The third criterion used regards the safety and autonomy of the system. As a concept UFOWTs like other offshore wind turbines are expected to be unmanned systems that should therefore not require consistent maintenance, checks or input for regular operation. Selection of the most stable and safe components for offshore navigation or use of higher reliability designs for the energy conversion systems are examples of how this safety and autonomy criterion is used for the design selection. When picking between types of technologies and routing methods the Operation and Maintenance (O&M) of these systems should be considered.

3.2 Operational Area

Two separate regions were investigated for deployment of UFOWTs, to explore and consider different geographical, economic, metocean and social factors which may facilitate or deter interest and effectiveness of MOWTs. The first region is the North Sea and the second the Mediterranean Sea. The following section assesses both areas with three criteria: potential for wind energy, existing infrastructure of interest and metocean patterns. The aim of the analysis is to determine the optimal operational areas and to consider realistic challenges of technology implementation that may not be covered in the modelling itself.

3.2.1 North Sea

The North Sea is an obvious choice for consideration for MOWT technologies, as it has been a global leader in the deployment of offshore wind turbines ever since the first offshore demonstrator project in 1991 [6].

Wind Energy Potential

The North Sea region is located on the European continental shelf and excluding the Norwegian trench off the coast of Norway, features relatively shallow waters throughout the sea region enclosed by the UK, Dutch/German and Norwegian coast. It is more than 970km long and 580km wide, offering a variety of wind sites across its waters. Figure 12 shows the Bathymetry of the North Sea seabed, which next to Figure 13 that shows the historically averaged wind speeds demonstrate how wind potential increases further from the coast in deeper waters. For use of fixed foundations only the area near the Belgian, Dutch, German, Danish and UK coasts highlighted in red to yellow in Figure 12 are feasible given the current monopile water depth limit around 50 to 60m [48]. Beyond the coast there is a need for deepwater foundation, which has given opportunity for floating foundations to enter the North Sea market off the coast of Norway.

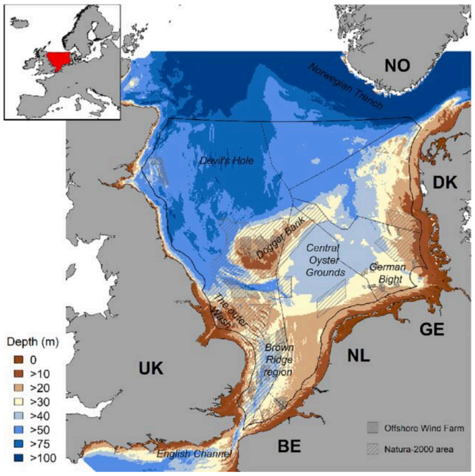

Figure 12: Bathymetry of North Sea, water depth shown in meters [49]

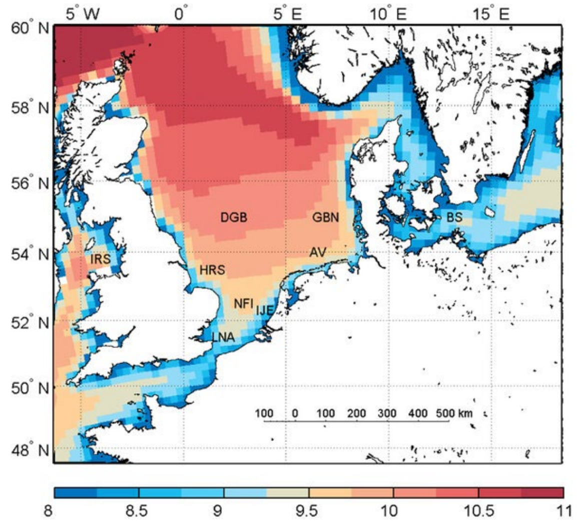

Figure 13: Average wind speeds for North Sea region, colored legend units in m/s [50]

From assessment of where current wind farm projects are located and where there is further potential for wind energy harnessing, the central area of the North Sea appears to be a promising area to investigate. Placing a UFOWT in the area where water depth is more challenging for monopiles and there are greater wind speeds could demonstrate the feasibility of the concept and allow for comparison with fixed foundation turbine operation.

Infrastructure and Other Economic Activity

Beyond potential for wind, there is a need to assess other activities occurring in The North Sea that would rend the operation of a UFOWT unfeasible. The North Sea legislation governs all the North Sea waters, while specific Exclusive Economic Zones (EEZ) may have additional laws and regulations. Figure 14 shows the EEZ regions that divide the North Sea, which may act as a deciding factor for the operational area of the UFOWT if certain laws would restrict its operation or permitting. Certain works in literature investigating unmanned UFOWT concepts have already identified the importance of EEZs in possible future implementation of these technologies [40].

A second factor to consider is the availability of ports for maintenance, accessibility and re-fueling. As seen in Figure 15, most of the ports on The North Sea are located on the Belgian, Dutch, German and Danish coast side. As discussed in the previous section, this region is already a popular area for use of fixed foundation wind turbines, so the area that would be more interesting to investigate is east of coast of the UK. There are several ports both in Britain and in Scotland that could serve as bases for the start of operation of the UFOWT and maintenance points that could reach the UFOWT system if needed or have the UFOWT reach them.

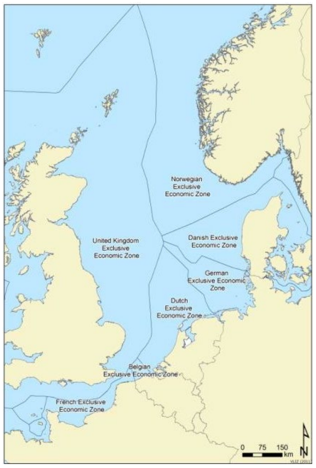

Figure 14: Exclusive economic zones in the North Sea [51]

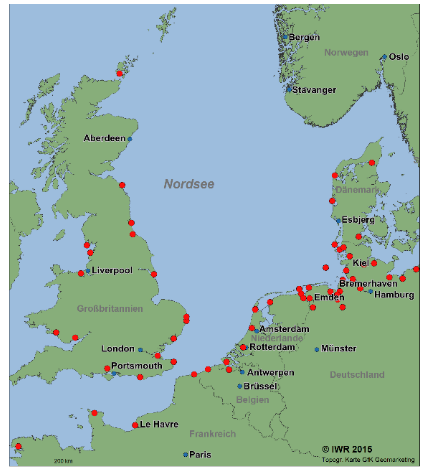

Figure 15: Ports surrounding the North Sea region [52]

Vessel traffic was another factor considered when selecting the operational area. Having an unmanned UFOWT vessel poses many risks for other vessels moving in the North Sea. Currently there are developments running in the autonomous vessel technology realm but the legal framework for these vessel types is still being constructed [53]. As of now, studies of UFOWT operation would be preferrable in an area less used for frequent ship transit. Annual traffic patterns for the past three years in the North Sea are shown in Figure 16.

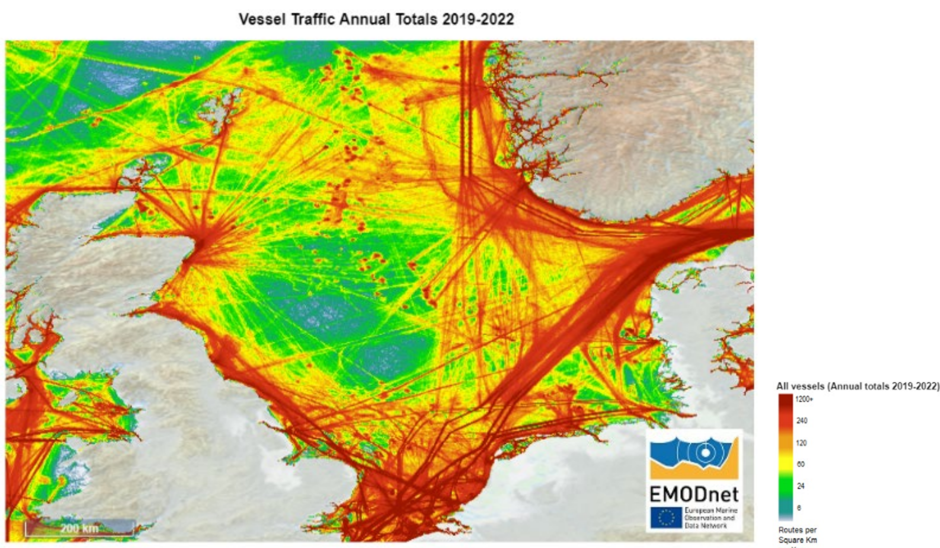

Figure 16: Annual vessel travel density in the North Sea for years 2019-2022. [54]

From the trends of ship traffic, the area around the Belgian border and all along the coast until Denmark is quite frequented and would be better avoided by a UFOWT system. The region previously mentioned off the coast of Scotland where there are a few ports, deep waters, and better wind conditions than the shallow water wind sites, appears to have decreasing traffic further from the coast. Practical solutions such as towing could allow for the UFOWT systems to be brought from the trafficked coastal area near the Scottish ports to a less frequented region. Further limiting the operational area of the UFOWT system to only one EEZ could resolve issues related to permitting and legislation. As of now the proposed operational area lies in the British EEZ.

Metocean Conditions and Patterns

The next factors to consider are the Ambiental ones that would influence UFOWT operation in its area. These were thought to be seasonal wind patterns, current patterns, and seasonal temperature variations. Temperature variations would become relevant when considering influence on fuel conversion efficiency, on board freezing or other component operation that is dependent on temperature. With respect to tides, the North Sea has three amphidromic points where there are no tidal effects approximately on the trajectory connecting the Norwegian coast to the Belgian one, considering the unmoored nature of UFOWT systems though tides were deemed to be negligible to system operation. When it comes to water current patterns, these may become significant for the energy expense of systems dynamically positioning the UFOWT or navigating in specific directions in case the water current is counteracting this movement. The typical current patterns seen in the North Sea are shown in Figure 17.

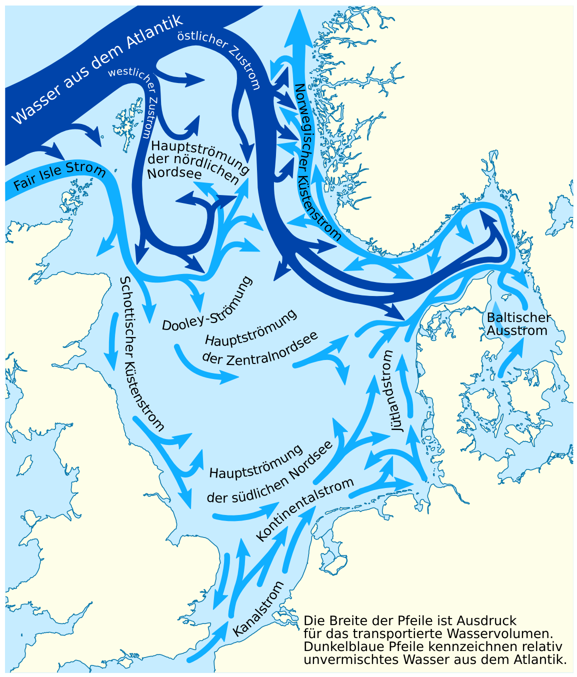

Figure 17: Map with prevailing currents in the North Sea [59]

The strong Norwegian current coming in from the Atlantic and running into and out of the Skagerrak straight between the Norwegian and Danish coasts immediately hints at this region being unideal for the operation of a floating structure assuming this current may have effects on the surface at points in time. In the rest of the North Sea area the Northern section has an average Southern flow of current which then interacts with the incoming English Chanell current coming from the South-West to cause multiple current gyres to form near the Scottish, British, and Danish coast. For the operation of a UFOWT the regions which have a fixed directional currents may prove problematic as UFOWT movement against the current may cause significant system energy losses. Meanwhile, the presence of gyres and changing current directions may facilitate UFOWT movement if these were considered in the routing and operation (this is not considered yet in this thesis project).

The wave climate in the North Sea is heavily dependent on the seasons, which is also related to the seasonal changes in wind that create higher waves. In the winter periods the average significant wave heights across the area off the coast of Scotland range from 1 to 3.5m. The wave height averages increase towards the North and the direction patterns show that wave direction is primarily North to South, while it is more varied during the summer month with average wave heights under 2m [56].

Selected Area

The approximate selected area for operation in the North Sea is shown in Figure 18 below, where a map is annotated with the limits of operation and the limits in which weather data is extracted.

Figure 18: Annotated map of the North Sea with the selected area for data extraction (dotted red line) and UFOWT system operation (solid yellow line) [57]

As discussed previously in this subsubsection, the sea region off the coast of Belgium, The Netherlands and Germany is disregarded due to the high traffic and already frequent use for fixed foundation wind turbine farms. The region closest to the Norwegian coast is also neglected given the expected presence of strong currents which will not be modelled, other regions are also neglected for their vicinity to other coasts. This area of operation seeks to offer a range of wind sites spanning mostly in the latitude direction and providing mostly far offshore locations. This will be used as a starting point in the modelling step, after which a more realistic limit on the operational area can be drawn based on the routing algorithm design and other considerations. The starting point for simulations is marked in a green circle which is off the coast of Scotland where the Aberdeen port is located.

3.2.2 Mediterranean Sea

With recent emerging projects and interest in floating wind energy in southern Europe, discussed also in events at WindEurope 2023, the Mediterranean Sea is another area that may be used to investigate use of MOWTs. This subsection looks at the wind energy potential, meteorological patterns, infrastructure, economic activities, and traffic in the Mediterranean. The different geography of the Mediterranean with a greater range of countries and distribution of islands creates different challenges than the North Sea.

Wind Energy Potential

Although the Mediterranean sea has significant wind potential, shown in Figure 19 by the historical mean wind speeds, the deeper water level shown in Figure 20 rends jacket and monopile foundation use for wind turbines technically unfeasible in most regions since they have a water depth exceeding 2000m.

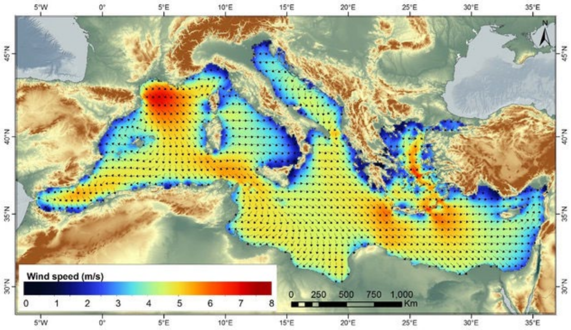

Figure 19: Mean wind speeds in Mediterranean Sea region [58]

Figure 20: Water depth map of Mediterranean Sea region [59]

It's seen that there are mean wind speeds around 5-7m/s at sea level in most open sea sections away from coasts. It would be useful to identify two separate regions, in the east and west Mediterranean, approximately divided by Italy's peninsula. Between these two regions, the water depth does not significantly change away from the coast, and the average wind speeds show to have higher values far offshore. There are a few areas where wind speeds show higher averages just South of the coast of France, near the Straight of Sicily and around the Greek islands and just South of these.

Infrastructure and Other Economic Activity

Compared to the North Sea, the Mediterranean has many more EEZ and less area in each one of these as well, as seen by Figure 21. If crossing different EEZs were to be problematic for implementation of this technology operation in the Mediterranean may require a stricter and smaller bound for operation, especially since there are some EEZs of non-EU countries in the southern section, for which marine laws and regulations applicable to UFOWT may change. Figure 22 shows the major ports surrounding the Mediterranean Sea with indication on their relative size.

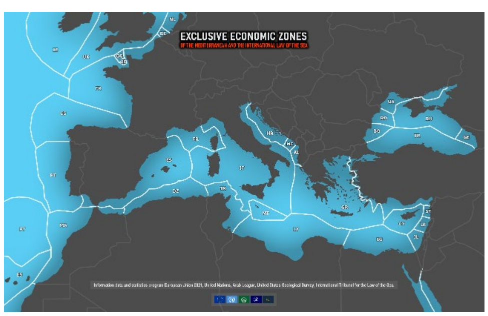

Figure 21: Exclusive economic zones in Mediterranean Sea Region [60]

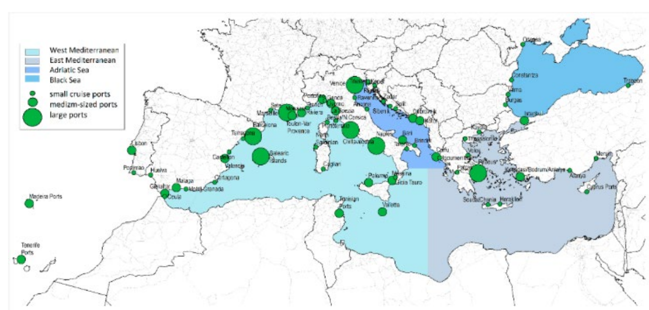

Figure 22: Relevant ports in Mediterranean Sea Region [61]

Regarding the port placement in the Mediterranean region, the coast of France and, Spain and Italy all offer multiple large ports which could potentially host maintenance or refueling of UFOWT systems. The eastern Mediterranean section instead has fewer options, the largest port Piraeus in Greece and does not have supporting ports in the southern section of the regions on the North African coast.

From the ship traffic data shown in Figure 23, the Mediterranean appears to have multiple and more narrow transit sections frequently used, which may rend UFOWT operation more complicated when avoiding encounters with other vessels.

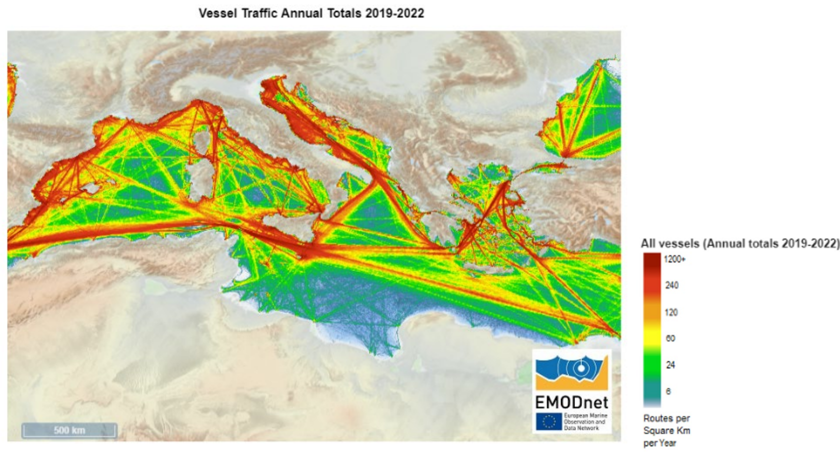

Figure 23: Annual vessel travel density in the Mediterranean Sea for the years 2019-2022 [54]

Given the transit frequency around the island of Sicily, it would likely be better to avoid this area and rather look at two separate regions to the east and west of the Italian peninsula.

Metocean Conditions and Patterns

Considering tides first, the Mediterranean Sea has very limited tidal effects as it is generally landlocked. The tidal effects of this region are even lesser than the North Sea given the reduced interaction with the Atlantic Ocean [64]. The current patterns in the Mediterranean are shown in Figure 24 show currents primarily running along the continental coasts with gyre formations forming farther offshore.

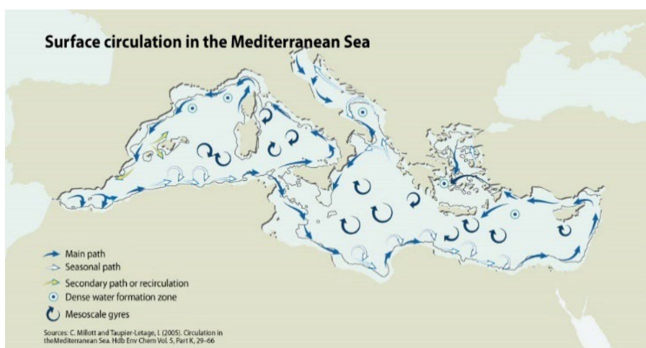

Figure 24: Surface circulation in the Mediterranean Sea categorized by main path, seasonal paths, and presence of mesoscale gyres [63]

The yearly averaged in the Mediterranean region are highest in the summer period and the 50th percentile annually averaged waves tend to stay under 1.5m. In the summer the 50th percentile of waves instead is below 1m in most of the Mediterranean except for the region south of Turkey and Greece which has on average seen higher waves with an annual average just under 1.25m [64].

Selected Area

Based on the analysis of the Mediterranean Sea area, two regions were selected to simulate UFOWT operation. These are shown in Figure 25 and Figure 26 below and will be referred to as “West Mediterranean” and “East Mediterranean” regions. The outer blue rectangular perimeter

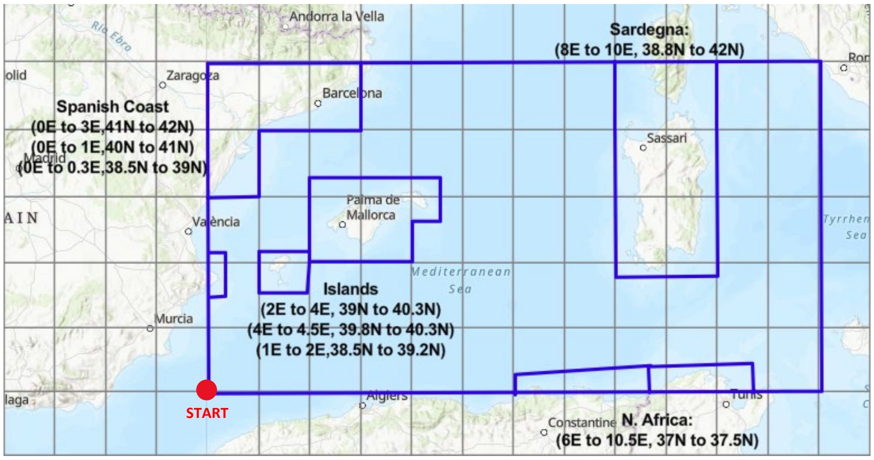

Figure 25: Selected operational area for the Western Mediterranean area

In the Western Mediterranean region the presence of islands complicates some of the routing operation since passage in between the coast of Spain and its islands requires very particular directions and navigation. This may create the need for a command within the navigation control unit to direct the UFOWT system through the sea area between the coast and islands if the UFOWT system becomes confined by coasts on two sides. The same is true for the region east of Sardinia, which would require the UFOWT to travel south for a section if it decides to move west in a short period of time. Beyond limiting the system in terms of areas where it cannot move to, this specific geography puts time limits on the decisions it may make on routes, since it would need to consider the time it takes to run the perimeter of an island and not just the direct displacement to a point that lies beyond an island. The starting point of the simulations is marked in the red dot at the southwestern limit of the operational area, to simulate a likely operation in which the UFOWT would be towed from the Spanish coast to its approximate starting point.

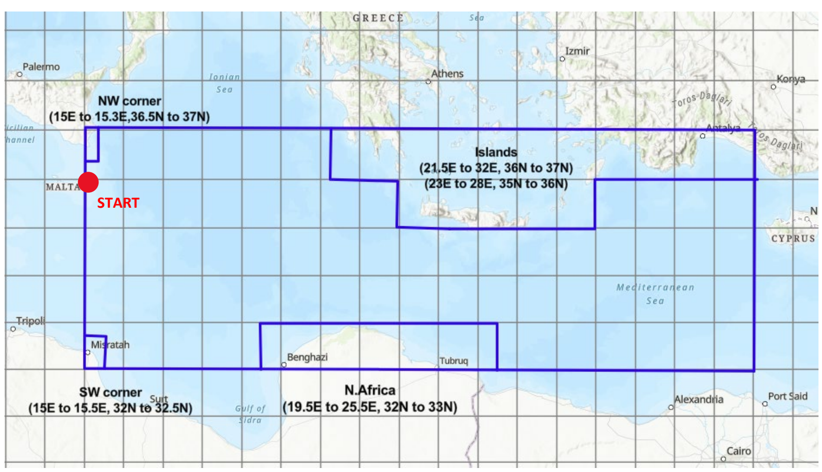

Figure 26: Selected operational area for the Eastern Mediterranean area

The Eastern Mediterranean region instead does have the same issues with islands since the entire region of Greek islands was disregarded for the operational area. This operational area extends more along the longitude of this Mediterranean region, taking advantage of wind speed differences mostly west to east. The starting point for operation and the simulations is marked with a red dot and is just off the coast of Malta and near the Sicilian ports.

3.2.3 Future Developments

The analysis and assumptions made in this section follow the status of development of economic activities and does not consider future developments and commitments to grow offshore wind energy. Given the take-off that wind energy is having in Southern Europe now, the market and infrastructure still needs to change in the upcoming years. Trends and predictions on this can be made by looking at the discussions brought forward at industry conferences such as WindEurope, where the largest and most influential stakeholders in the wind energy industry meet and discuss the current and future barriers to wind energy.

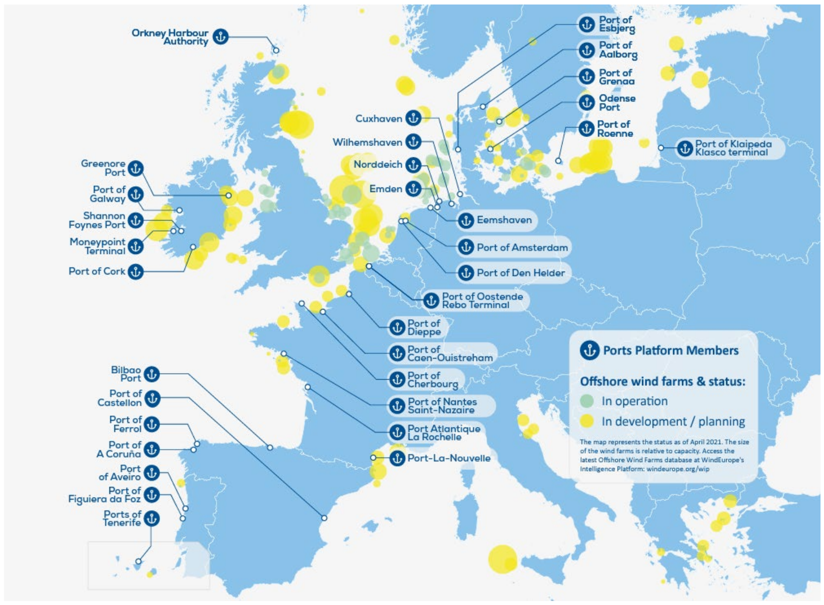

Figure 27: Ports expected to play a key role in the future of wind energy supply chain in Europe [67]

From above, the feasibility and technical support difference between the two selected sea regions for UFOWT operation is evident based on the amount of wind farms in development and current port platform members committed to supporting offshore wind. The Mediterranean is behind in terms of ports platform members and already existing wind farms in the area, which creates uncertainty on the timeline in which a UFOWT system may be able to be tested. It could be assumed that UFOWT considerations in the Mediterranean Sea will need to follow proof of concept of floating wind in the Mediterranean or UFOWT proof of concept elsewhere. The port requirements for a UFOWT system may be another limiting factor that

3.3 System Components

This section explains how each component of the UFOWT system was chosen and the specific parameters input in the model detailed in Chapter 4, including the wind turbine, foundation, propellers, and energy conversion technologies.

3.3.1 Wind Turbine

For the wind energy conversion technology to be mounted on the mobile foundation, the choice fell between the different technologies presented in literature and proposed for MOWE systems or other systems currently used outside of the MOWE domain. Using all three design choice criteria described in Section 3.1, a HAWT wind turbine was chosen to follow the industry trends for offshore energy conversion. Additionally, in some literature research the assessment was made that HAWTs present a simpler stability problem for a MOWT than a VAWT since HAWT UFOWTs. When considering the power rating of the turbine the following were investigated as factors: power ratings of literature proposed systems, current trends in proposed unmoored floating offshore wind turbines, available reference turbines. A turbine rating and system comparing to the current offshore wind turbine trends beyond the 10MW threshold was intentionally avoided given that this project does not dive into the specifics of stability of the system, so it was rather preferred to keep investigations on a smaller scale system that could be then scaled up in further research and coupled with investigation into stability effects. Table 3 below summarizes the turbine specifications and parameters used to model the turbine system.

Table 3: NREL 5MW Turbine specifications and characteristics [66]

Parameter	*Value*	*Units*
Power Rating	5	MW
Cut-in Speed	3	m/s
Rated Speed	11.3	m/s
Cut-out Speed	25	m/s
Hub Height	90	m
Rotor Diameter	126	m
Rotor Mass	110000	kg
Nacelle Mass	240000	kg
Tower Mass	347460	kg
Total Mass	697460	Kg
Assumed values:		
Power Coefficient	0.482	-
Induction Factor	0.33	-
Drivetrain Efficiency	94.4%	-

The power rating of the turbine along with the cut-in, rated and cut-out wind speed along with the assumed values at the bottom of the table are used to build the power curve needed in the working model to estimate different power outputs depending on the wind conditions. This power curve can also be used to make estimates and forecasts on power production given the wind condition forecasts and is shown next to the NREL provided specifics on the NREL 5MW wind turbine in Figure 28 and Figure 29.

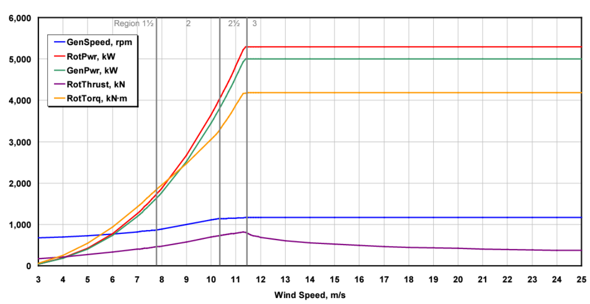

Figure 28: Steady state responses for the 5MW NREL wind turbine [44]

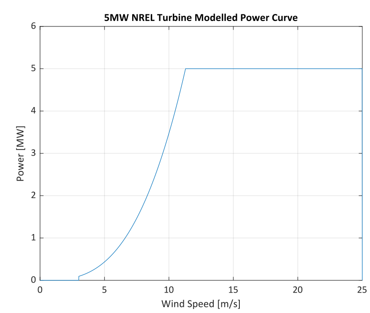

Figure 29: Modelled wind turbine power curve

A limitation with using a conventional wind turbine assuming no alterations are made to the blades or operative methods is that the system must be operated by attempting to simulate conventional use as much as possible. What is meant by this is that when there is incoming wind at an angle to the rotor, the system should be re-aligned with the wind, which has a variety of solutions including active or passive yaw of the rotor or even yaw of the entire foundation.

3.3.2 Foundation

The foundation of the MOWT is critical to system operation since it provides the necessary stability depending on the intended routing and operational method. The foundation design goes hand in hand with the routing method design along with design of other onboard components. For instance, the turbine size and other component weights may place stringent requirements on the stability and weight support that the foundation must provide, especially considering the moments created by the turbine thrust at a certain height above the foundation elevation. The intended routing method would also influence what sort of foundation is needed, as frequent movement in the seas would call for a more streamlined structure.

For the dynamic positioned system, a barge foundation was selected, specifically one described and modelled in literature which was scaled to a 5MW turbine system [38]. Meanwhile a trimaran foundation was explored for the ADOWT system, given the higher stability for sailing those three hulls provides. Although system stability and hydrodynamics fall outside of the scope of this thesis project, the foundation parameters and characteristics are used to model the water frictional losses for movements. The drag force, F_w, applied by each foundation is calculated with formula (12) using the frictional coefficient, C_f, calculated with formula (13).

$$F_w = \frac{1}{2}\rho_w V_v^2 A_w C_f \tag{12}$$

$$C_f = \frac{0.075}{log_{10}\left(\frac{V_v L}{v} - 2\right)} \tag{13}$$

Where ρ_w is the seawater density (assumed to be *1028kg/m³* for seawater at average North Sea yearly temperatures while *1025kg/m³* for Mediterranean Sea water temperatures annual averages) [47] , V_V is the speed of travel of the system and A_w is the wetted area. *L* is the characteristic length of the foundation used to calculate the Reynolds number and *v* is the kinematic viscosity (calculated by dividing the assumed dynamic viscosity of *0.00167Pas* for the North Sea or *0.00111Pas* for the Mediterranean by the respective water density) [48]. The wetted area, A_w, of each foundation type is estimated by approximating the barge to a cuboid shape and the trimaran hulls to three semi-cylinders as seen in Figure 30.

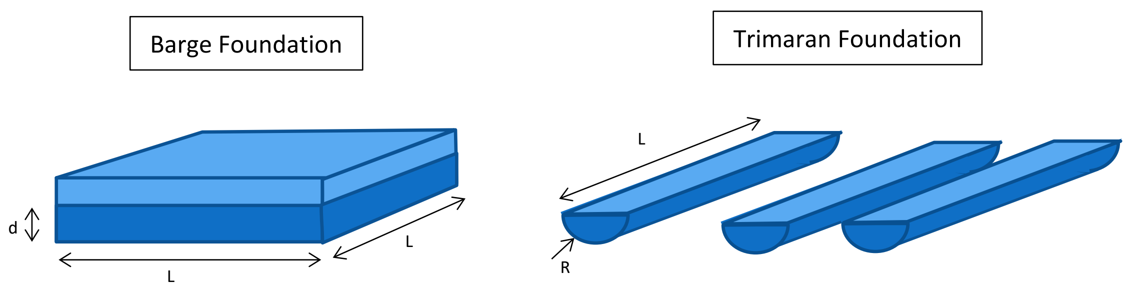

Figure 30: Barge and Trimaran foundations modelled to calculate the wetted surface area, showing characteristic length, L, draught, d, and radius of hull cross sections, R. Shaded sections show the estimated and considered wetted area.

Barge

For the barge foundation the characteristic length, *L*, is scaled from a foundation used by a 2MW turbine from 40m to 100m. The wetted area is estimated by equation (14), given the cuboid approximation shown in Figure 30.

$$A_{w,barge} = 4dL_{pp} + L^2 \tag{14}$$

The wetted area of course is dependent on the draft, d, of the foundation which changes based on the weight load applied. The draft is estimated with the following formula (15).

$$d = \frac{\Delta V_{barge}}{L^2} = \frac{M_{disp}}{\rho_w C_D} \tag{15}$$

Where V_{barge} is the displaced volume of water by the foundation, determined by the displaced mass, M_{disp}, which is calculated by approximately adding the masses of the on-board system components, such as wind turbine and energy conversion, storage, and fuel.

Trimaran

The wetted area of the trimaran is estimated by approximating the three hulls as equally sized semi-cylinders that give a total wetted area described by equation (16) which requires the equations (17) and (18) for the approximated semi-cylinder radii and the displaced volume by the foundation.

$$A_{w,trimaran} = 3\pi R^2 + 3\pi RL \tag{16}$$

$$R = \sqrt{\frac{2\Delta V_{trimaran}}{3\pi L}} \tag{17}$$

$$\Delta V_{trimaran} = \frac{3}{2} R^2 \pi L = \frac{M_{disp}}{\rho_w C_D} \tag{18}$$

Both foundations can be modelled this way in terms of the drag loss that they incur the overall system for movements in water at a given ‘boat velocity’ V_b.

3.3.3 Propellers & DPS

The propellers for the system were not chosen beforehand since the rating of these was still unknown and common ratings proposed for UFOWTs were not widely mentioned in literature. Instead, it was left for after the system modelling to pick the propellers based on the power needed to move each of the systems according to the routing movements and requirements. Regarding the propeller type it was found in literature that based on the required application of stabilization and maneuverability a choice/combination of azimuth mounted and/or cycloidal type propellers which are frequently used in DPS while for navigation a screw propeller would likely be more suited [27].

The methodology used to estimate the propeller power consumption is similar to that commonly used in UFOWT literature to estimate the power losses of moving UFOWT systems [31, 16]. This involves a force balance model of the UFOWT system that is assumed to be in steady state between the propulsive force of the propellers pushing the system forwards in the desired direction and the drag forces acting in the opposite direction. It is assumed the water drag forces on the foundation contribute the majority of the drag force sum which are calculated with equation (12) from the previous subsection 3.3.2.

When it came to estimating the power consumption of the DPS stabilizing the system producing electricity while fixed in position, some of the methodology presented in the literature involved another force balance equating the force applied by the DPS systems to the thrust force applied on the wind turbine by the incoming wind. In the first attempt to model this using the conventional actuator disk theory thrust force equation (5) yielded thrust values that exceeded the thrust force curves presented by the NREL 5MW turbine [66] which should stay below 1000kN as seen by Figure 28 and has peak at the rated wind speed. An alternative to modelling this power loss was found to be drawing on literature work that solely focused on DPS energy cost modelling to estimate the cost for this thesis project. This was done using a paper which investigated a range of wind turbines from 3-7MW and range of DPS thruster diameters to determine the power ratio of the generated and consumed power of the overall UFOWT system [XU]. For a 5MW or approximate 120m diameter turbine rotor, the power ratio was found to be 0.5 (without the consideration of current on the system costs). This was thus used as an approximate cost of the DPS system for all regions. This assumption is limited in considering the effects of currents on system costs which are expected to amount to a higher value of 0.8 of the generated power for the North Atlantic example region and depends on the site.

3.3.4 Energy Conversion and Storage

For the storage of electric energy produced by the turbine, there are a variety of options which were introduced in the previous chapter, for use on or offshore alongside wind turbines or other variable generation renewable resources. Hydrogen production through electrolysis was chosen for the energy conversion to follow with the industry trend of investment in hydrogen conversion. Within the conversion methods, technological readiness was prioritized which left the choice between the most developed options of PEM and Alkaline electrolyzers. Between the two, PEM electrolysers much quicker degradation compared to Alkaline ones justified the choice of an Alkaline one to provide a more autonomous system in terms of O&M requirements [69]. The use of hydrogen conversion using an alkaline electrolyser requires a water input and outputs a stream of hydrogen and oxygen. For the scope of this project, the capacity, efficiency, and production rate of the electrolyser are used to approximate the energy conversion from electrical to chemical form. The use for output oxygen and additional subsystem dealing with water extraction, filtering and desalination from the sea are disregarded.

The capacity of the alkaline electrolyzer was chosen to match the turbine 5MW rating and the relevant parameters of an example of such electrolyzer as the HELA1000 model [70] are presented in Table 4 below.

Table 4: Characteristics of HELA1000 5MW Alkaline electrolyser [70]

Parameter	*Value*	*Unit*
Tech type	Alkaline	-
Rated power	5	MW
Efficiency	78	%
Start-up time	20	min
Water consumption	900	L/h
H_2 gas production	1000	Nm^3/h
O_2 gas production	500	Nm^3/h
Output pressure	1.6	MPa
DC power consumption	4.4	kWh/Nm^3H^2
Lifetime	80000	Hr
Operating range	30-110	%

The parameters used for estimation of the hydrogen production are the system efficiency, H_2 gas production rate and operating range. It will be assumed that when the turbine is producing below 30% of its capacity then that electricity would be redirected to power or charge other components since that is the lower limit of the electrolyser operating range. The DC power consumption is used to estimate the onboard energy costs, which will add onto the propulsion system energy costs. The start-up time will not be integrated in the model but will be considered to make recommendations on further control methods of UFOWT systems depending on the routing system used.

For the storage of energy, it is expected for the system to have at least two separate energy storage means, where only one is allocated to storage of hydrogen production directly from the wind turbine system. The remaining energy storages are meant to provide a certain level of autonomy for the system so that the onboard components may operate even without the wind turbine generating electricity. This includes the propulsion system, dynamic positioning system, onboard control, communication systems and power management units amongst others. To avoid losses and requirement for bulky conversion components on board, these auxiliary power sources are chosen as electrochemical storage in form of lithium-ion batteries. The sizing of these batteries is outside of the scope of the project since there is a wide range of components that need to be modelled and estimated in terms of their electricity consumption requirements. The choice between storage methods for the turbine produced hydrogen fell between keeping hydrogen in its elemental form in either liquid form or gaseous form pressurized between 350-700bar or in material-based forms [71]. Prioritizing CGH2’s higher efficiency as a storage means, the choice was made to keep hydrogen in its gaseous form and so employing a compressor onboard to store the electrolyser product in high pressure tanks on board. The hydrogen quantities produced by each system were calculated by first subtracting from the energy yield the energy allocated to movements, lost to drag forces. Secondly this “net energy” was multiplied by a set of efficiency values that considered energy lost or consumed by other components. Some of these efficiencies are described in Table 5 below.

Table 5: Efficiency quantities used for calculations of final hydrogen production of the two UFOWT systems.

Component	Description	Value
Drivetrain	Assumed efficiency of drivetrain of 5MW NREL turbine.	0.944
Electrolyzer	Efficiency of chosen electrolyzer in outputting the inflow of electrical energy in form of hydrogen gas	0.780
DPS	Dynamic Positioning System employed by the barge foundation UFOWT, assumed from literature work modelling these costs.	0.500

Some disregarded components would still be relevant in the conversion are the electrical converter and rectifier that would need to be selected based on the power requirements of other onboard components, such as the onboard controller system, short term battery storage, compressor, water pump and storage control system amongst others required to sustain fuel conversion.

3.4 Routing Methods

Among the reviewed routing methods seen in literature and discussed in Subsection 2.3.5, two main categories were identified of moving and fixed operation, so a routing algorithm of each type was chosen to be developed. The first is the routing algorithm referred to as "Alternating Navigation and Generation" (ANG) and used with dynamically positioned UFOWT systems and designs, while the second is the "Continuous Navigation and Generation" (CNG) algorithm used with UFOWT systems designed for navigation with vessel-type foundations. The differences between the two routing algorithms are compared in the following Table 6 which looks at algorithm search objective, constraints, search frequency and safety limits.

Table 6: Qualitative characteristics of each UFOWT routing method: ANG and CNG

	Alternating Navigation/Generation	*Continuous Navigation/Generation*
Objective	Locate ideal energy production location for next set of generating hours	Follow downwind direction
Constraint	Minimize travel energy expense to the next location	Minimize frequent maneuvers Only travel when wind speeds are greater than the vessel moving speed
Search Frequency	Every *S* number of hours, equivalent to number of hours spent stationary	Every hour during movement when decisions on movement/stationary position needs to be made
Safety Limits	Coastal, operational area, waves	Coastal, operational area, waves

Although the objective of both routing methods is similar in the sense that they consistently seek the optimal wind conditions, due to the working principal differences between the designs the algorithms determine these "optimal conditions" in different ways. The ANG algorithm generates electricity while staying still so it would benefit most from sites with wind speeds above the rated speed of the wind turbine to produce the rated power. On the other hand the CNG has more limitations on when it may move since its route is dictated more by the changing wind directions, so it would prioritize more producing energy which requires a wind speed above the sum of the turbine cut-in wind speed and the travelling system speed. The search frequency for the two systems is set differently, since the ANG forecasts locations that locations that are safe to remain fixed in and produce energy for a set of hours, it only needs to make decisions every time the set hours of operation have elapsed. Meanwhile the CNG algorithm needs to correct its route in response to changes in the wind direction, due to data availability limitations, for this designed algorithm this is assumed to be every hour. The safety limitations placed on both systems is the same, requiring it to consider coastal areas and their surrounding sea zone no-go's, remain within the defined operational area and avoid any unsafe waves along the route.

3.5 System Overview

The chosen UFOWT system can be approximated in terms of its components and interactions between these by the system block diagram shown in Figure 31, where the overall system is divided into three subsystems: the wind turbine, onboard and fuel subsystems. The interactions between each subsystem or subsystem block are either in form of electricity, commands, mass flow or information. The electricity network includes both AC and DC electricity flow although there are distinctions in reality (before and after the converter), the mass flow occurs in form of sea water, desalinated water, oxygen, hydrogen, and wind (where the hydrogen also changes pressures, but this is not specified in the block diagram). The inputs come from the sea environment and are wind and sea water, whereas the overall system outputs are oxygen and the non-included energy losses/heat.

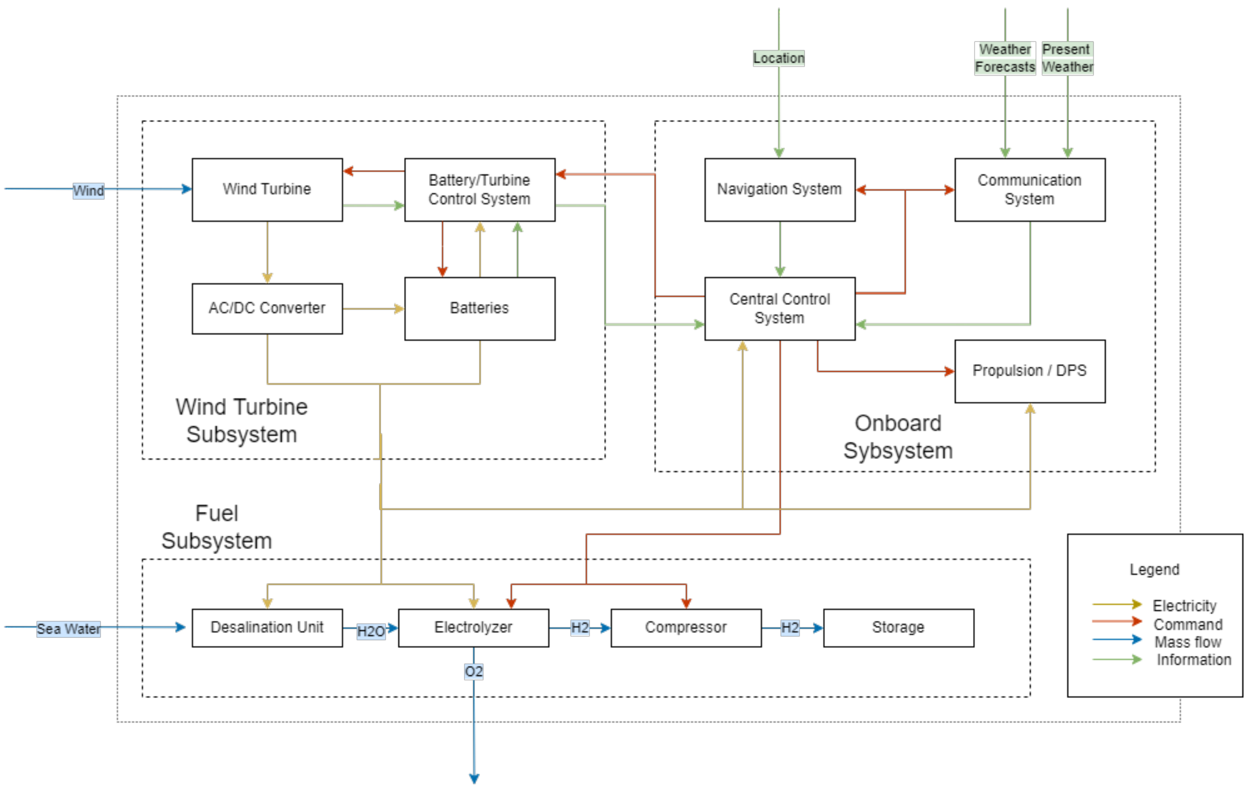

Figure 31: System block diagram describing a simplified interaction between different onboard units of the UFOWT system

The wind energy input is used by the wind turbine unit to convert this to electrical energy, which starts the network of electricity flow. This alternating current (AC) is converted to direct current (DC) by a converter and the remaining network of electricity flow is assumed to run on DC. The wind turbine powers the onboard battery system which is meant to provide energy to all the units onboard which require operation even when there is no wind. These include the navigation system, the control system (which includes control of the wind turbine, electrolyzer, compressor, propulsion system and storage system). The navigation unit on the bottom of the diagram requires three main inputs which are the system location, current weather conditions in the surrounding area and forecasted weather data which are assumed to be incoming communication from land weather stations. Along with receiving the weather forecasts and weather data, the communication unit from land also serves the function of collision avoidance with other vessels or coast or land areas.

Although it is not covered in the scope of this project, it is expected that the power management along with the control unit onboard would be designed to make decisions on which energy source shall be used to power specific components (either the onboard battery or wind turbine system when it is in operation). This would likely depend on multiple decision factors such as the battery state of charge, the power output of the wind turbine, forecasted weather conditions hours ahead and distance from the nearest port.

Alternatives or possible additions to this system to make it more resilient and autonomous may include a backup engine for scenarios in which there are faults in the system or wind droughts. Since the system as described above is entirely powered and fueled by wind energy, hybridizing the system by adding a solar photovoltaic system would allow for the solar resource to be harvested too. This addition would strengthen the system by providing two different types of renewable energy sources to fuel the energy consumption on board, and specifically a renewable energy source which compliments wind energy in terms of availability, since solar energy is more abundant on average in the warmer months during which wind energy reduces in availability. Benefiting from similar advantages are systems that employ wave energy converters which could be a method of increasing the net energy yield during fixed operation of UFOWT systems.

4 Modelling & Methodology

This chapter follows the system design to explain how the modelling environment was set up and how simulations were conducted. Section 4.1 first covers the type of weather data was used in the model and how it was implemented. Section 4.2 then outlines all the data-processing steps that were taken to set-up the modelling environment in an efficient manner that allowed for large amounts of data to be handled. Section 4.3 explains the development of the routing algorithms and their working principle.

4.1 Wind & Metocean Data

To test the system operation and routing algorithm, it was thought to use real past weather data to simulate hourly changing weather which changes across seasons and years. A dataset for both North Sea and the Mediterranean was searched with the same variable types and same data precision to allow for a direct comparison across the different locations. For this intended use, the ERA5 hourly data [72] was found suitable given that it provides hourly weather data multiple decades back from the present for an extensive amount of weather variables. The weather variables extracted from the ERA5 dataset are outlined in Table 7 below with their variable name, unit, description and intended use in the routing algorithm.

Table 7: ERA5 extracted weather data types, description, and units

Variable	*Units*	*Description*	*Use*
Time	hr	Hour count from the prescribed start time of extracted data to the end. (e.g. 1-8760 for a year)	Data Processing
100m u-component of wind	m/s	Positive notation: air moving east. Resolution: 0.25° x 0.25°	Energy yield estimate
100m v-component of wind	m/s	Positive notation: air moving north. Resolution: 0.25° x 0.25°	Energy yield estimate
Mean wave period	s	Average time for two consecutive wave crests to pass through a fixed point. Resolution: 0.5° x 0.5°	Safety considerations
Significant wave height of combined wind and waves and swell	m	Average height of highest third of sea wave originating from wind and swell. Resolution: 0.5° x 0.5°	Safety considerations
Mean wave direction	degrees true	Mean direction of sea surface waves. Zero direction defined as waves coming from north. Resolution: 0.5° x 0.5°	Safety considerations

The data was extracted with the finest available resolution (0.25° for wind variables and 0.5° for wave variables) for the rectangular data areas described in Section 3.4 for the North Sea and two Mediterranean regions. The sub-region extraction function was used for the following limits for each region shown in Table 8 below.

Table 8: Sub-region extraction limits (in degrees) for dataset extraction from the ERA5 database

	North	*South*	*East*	*West*
North Sea	62	54	6	-2
West Mediterranean	42	37	12	0
East Mediterranean	37	32	32	15

Beyond these described variables, the overall wind magnitude and wind direction was calculated as needed using the east and north components of the 100m wind. The raw data could be extracted as either a GRIB or NetCDF file which required a data processing step prior to direct import into the MATLAB environment.

4.2 Data Processing

This section details the steps taken to import and process the ERA5 hourly data for final use in the forecasting, routing, and energy yield algorithms for the North Sea and Mediterranean regions. First, the required variables were imported for the desired time and geographical range, after which the data was processed and refined, involving multiple MATLAB functions. The R2021a version of MATLAB was used for all code development and running.

4.2.1 Data Import

With the functionality of the data processing code in mind, all variables from the ERA5 dataset were imported individually as 'NetCDF' files containing the data for every hour of a chosen year for the selected sub-region. The use of GRIB format was discarded for use with the MATLAB R2021a environment after some attempts which yielded errors in data conversion to 2-dimensional matrix format.

The objective of this initial data processing step is to allow for a quick import of weather data into the MATLAB environment for a single given hour. The command '*ncread (SOURCE, VARNAME, START, COUNT)*' can be used to extract matrices of specific variable data over the imported geographical region for specific ranges in time. The required inputs are the source file type (*SOURCE*), variable name (*VARNAME*) used in the .nc file, a vector of 1-based indices specifying the starting time of the data extraction (*START*) and a vector specifying the end of the extraction (*COUNT*). Miniconda was used to run python code useful for seeing the structure of NetCDF files, including variable storage order, size, and names. This was necessary for input *VARNAME* for the MATLAB *ncread ()* command, these are shown in Table 9 below.

Table 9: Variables and their respective names stored in NetCDF files extracted from Copernicus weather dataset.

VARNAME	*Variable description*	*Units*
time	Time	hr
u100	100m u-component of wind	m/s
v100	100m v-component of wind	m/s
mwp	Mean wave period	1/s
swh	Significant wave height of combined wind and waves and swell	m
mwd	Mean wave direction	deg

The above ncread () command was used to extract a single variables data over the geographical area for a specific hour of the year. This command was implemented in two functions that could be called to simulate extraction of wind and wave forecasts respectively and to estimate energy yield over time.

The result of the data import step as was done using the netCDF4 format was a MATLAB script that could import whichever desired hour of a year worth of wind or wave data from an external .nc file containing such data. The .nc files were organized to each have one year's worth of data for 2012-2021 and to all have the same sub-region extraction bounds (so the same latitude and longitude limits). From here, the imported hourly data was in the dataset predetermined level of resolution and order, assigning NaN value to data points that were missing. This required multiple data processing steps the first of which required ordering the weather variables using the north to south and west to east notation which would allow easy visualization and troubleshooting.

4.2.2 Coordinate Correction

Two main issues arose when checking the format of the imported data: the coordinate frame order of the stored data and the mismatch between resolution of wind and wave data. The red mark in the left-hand side of shows the maximum wind speed location, which corresponds to a location near the coast of the UK, while the missing data in the right-hand side wave plot represents the UK coast which is included in the search area. As is noticeable the order in which the latitude and longitude axes are placed, it is difficult to visualize the conventional globe and areas of the North Sea from these plots which makes it more difficult to evaluate where data errors occur and to ensure that wind and wave data are read for the same set of coordinates. To visualize and manually troubleshoot the way weather data is read within the code, the matrices containing all the significant wave heights, or the wind magnitudes were transposed to have increasing longitude coordinate values along the columns to the right and decreasing latitude values. Figure 32 below shows the corrected order of data and additionally shows the differences in data type for the imported ocean and wind variables in the search area. The ocean data is stored as "NaN" for locations onshore while wind data is provided for both on and offshore.

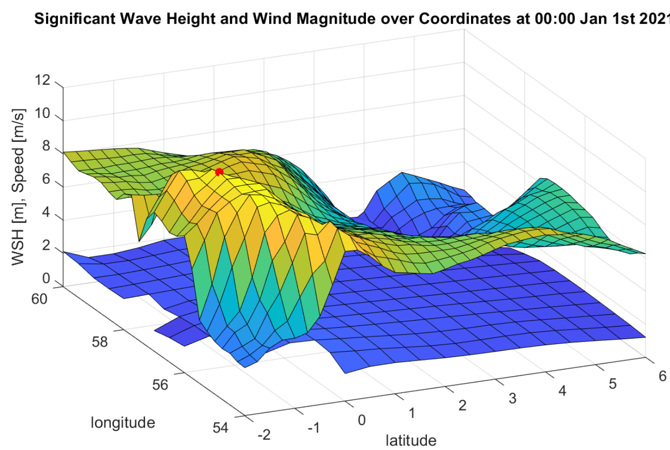

Figure 32: Wave and wind data displayed simultaneously for a given hour in the North Sea

Following the data import, the *u*- and *v*-components of wind are used to calculate the wind magnitude and its direction in notation using north as zero degrees, using conditional statements to maintain this zero north notation as seen in the code section below:

```
for r=1:length(wind_vel100)
        for s=1:length(wind_vel100)
                if ucomp(s,r)<=0 && vcomp(s,r)>=0
                        dir(s,r) = 360 + rad2deg(atan(ucomp(s,r)/vcomp(s,r)));
                elseif vcomp(s,r)<=0
                        dir(s,r) = 180 + rad2deg(atan(ucomp(s,r)/vcomp(s,r)));
                end
        end
end
```

The wind direction data was also ordered so that it could be coupled with the wind magnitude as is shown in Figure 33 below.

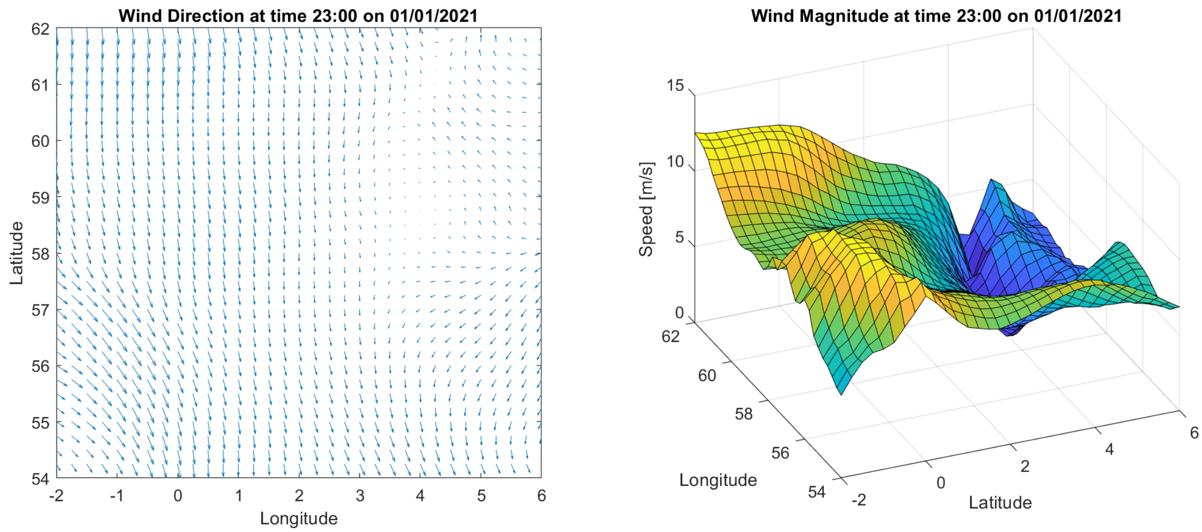

Figure 33: Wind direction and wind magnitude displayed for a given hour in the North Sea

The wind direction data was only used for one of the routing algorithms and so this processing step was not included when it was not needed to speed up the simulation time.

4.2.3 MATLAB Functions

Following these initial corrections of the imported data, some functions were developed to allow for easy and quick processing of data each time it was extracted from the .nc file, so that only the required data for the simulation was processed rather than the entire year or more's worth.

Function: geodata_refine

This function had the aim of altering the resolution of the data to interpolate more data points for the algorithm to work with but also to ensure that the wave and wind data had the same number of points. The difference in grid coarseness between wind and wave data were resolved by using the *interp2()* command in MATLAB. This allowed for the wave data to be further refined, approximating wave conditions in between the given data-points. The data-grid refinement step was handled in this separate function called "*geodata_refine*", which allowed for the initial distance between wave data-points of around 55.5km to be reduced to 7km between the fine-grid estimated points. Although this is an approximation done as so, it is expected that in a real application of UFOWT technology there would be much higher resolution of weather data available than the one offered by the ERA5 imported data. The use of the function also facilitated speeding up the computation time of the algorithms when a lower accuracy was needed, by using a lower "k-factor" by which the grid is refined. The effect on number of data points in each operational area given different k-factors is shown in Table 10, Table 11 and Table 12. The only required inputs for this function are the user-defined k-factor and data matrix that needs to be refined. Furthermore, this function did not need any adaptation to be used with data for the Mediterranean region.

Function: Deg2ind

Another widely used function in the methodology is the "deg2ind" function, which converts longitudinal or latitudinal degrees to indices of the weather matrix being handled in the code. For instance, if for a given hour the North Sea region wind values are imported into the MATLAB script and then refined to create a 2D 129x129 matrix of wind values, if it was necessary to extract the wind speed at a specific coordinate such as [57,-2], this function would be able to indicate that the desired wind speed is located in row 81 and column 1 of the weather matrix. Given the inputs of matrix data dimensions, rounding value, coordinate longitude, and latitude (in degrees), the function outputs the column and row indices corresponding to the location within the refined weather data matrix.

The rounding value is the coarseness of the geographical grid, determined during the refinement process, the data dimensions and coarseness values are shown in Table 10, Table 11 and Table 12 below for each geographical area used in this project.

Table 10: North Sea data dimensions and refinement steps

k-factor	*0*	*1*	*2*	*3*
Matrix Dimension	33 x 33	66 x 66	129 x 129	257 x 257
Grid coarseness (deg)	0.25	0.125	0.0625	0.03125
Data Points	1089	4356	16641	66049

Table 11: West Mediterranean Sea data dimensions and refinement steps

k-factor	*0*	*1*	*2*	*3*
Matrix Dimension	21 x 49	41 x 101	81 x 201	161 x 401
Grid coarseness (deg)	0.25	0.125	0.0625	0.03125
Data Points	1029	4141	16281	64561

Table 12: East Mediterranean Sea data dimensions and refinement steps

k-factor	*0*	*1*	*2*	*3*
Matrix Dimension	21 x 69	41 x 137	81 x 273	161 x 545
Grid coarseness (deg)	0.25	0.125	0.0625	0.03125
Data Points	1449	5617	22113	87745

The function was adapted for use with the Mediterranean region by including an if-else statement which would detect whether the input coordinates are from the North Sea, East, or West Mediterranean. The statement simply checked whether the latitude was above 50 to determine that the area being dealt with was the North Sea and otherwise checked whether the longitude was above or below 15 degrees to determine the difference between the east and west Mediterranean regions. Following this, a latitude and longitude array are created using the start and finish values determined by the operational areas in each geographical region, which respect the weather matrix dimensions being used in the main script. The function then rounds the input coordinate to the closest value in these arrays using the grid coarseness input value and finds the index of the latitude and longitude array which correspond to the rounded coordinate.

Function: safecoast

The safecoast function objective is to store all the information regarding the coastal and inland areas within the operational area. The use of a rectangular or even square search area for weather data handling allows for straightforward matrix operations but does not represent the actual allowable area for a UFOWT to navigate in. For this reason, safety limits need to be applied on the coordinate range in which weather data is still available. Two main safety limits were first implemented: the coastal area and the changing unsafe wave condition locations. This function specifically applies the coastal safety limits and requires the weather data dimensions being used in the main script to create a matrix with the same dimensions to output. To remove the possibility of the search algorithm reading wind on the coast as a viable location to move to, the available weather data was filtered by multiplying it with a “coastal matrix”. This matrix involves a set of ones and zeros, where the zeros are manually input to represent areas of the coordinate frame on or near land, while the ones approximate the navigable area enclosed in the operational area. The function is customized to each geographical region, since in the script the approximate locations of each land mass is specified to create the safecoast matrix.

A similar logic is used to implement safety limits during operation such as that of avoiding unsafe wave or storm areas. Since significant wave height data is available, this can also be used to create a safety filter on the search area, nulling any weather data in zones where the significant wave height is above the safety limit, the algorithm then only reads weather data that is safe when making its next movement decision. An initial guideline for an unsafe wave height value was used corresponding to 6 meters [40]. The simplest form of this safety implementation was to run a search of the maximum wind value for a given hour in the entire search area before and after the wave safety requirement was included to find the true safe optimal wind site.

Function: forecast_wind, forecast_wave & forecast_all

The first function *forecast_wind* requires two inputs and outputs a 2-dimensional data-matrix. The inputs *y* and *h* are the year and hour (measured from 1 to 8760 or 8784 for leap years), while the output is a matrix containing variable data points corresponding to different coordinates. The functions use the data import steps described earlier in this subsection to individually extract variables for a given hour from the NetCDF files containing weather information for years at a time. A switch statement is used within the function to determine which file be opened, which is determined by the year y in which the simulation is being run. For the wind forecast specifically first the u and v components are imported and following this the velocity magnitude is calculated within the function and the data is transposed to follow north to south and west to east notation. The same logic is applied to the *forecast_wave* function which only imports variables relating to ocean waves and processes them within the function. The *forecast_all* function was created later to merge these two functions in one when running longer time simulations. Importing the ERA5 data all in one file, this minimized the amount of .nc files that were opened each time the function was called and allowed for a faster run-time for the code.

These three functions are adapted to each geographical area by simply changing the names of the .nc files that are opened in the function to the names given to the other region's data files. The rest of the processing steps were the same for both the North Sea square data matrices and the Mediterranean rectangular matrices.

4.3 Routing Algorithms

This section describes the methodology for the development of the routing algorithms picked and presented in Section 3.3. For each of the two routing methods first the methodology for algorithm development is presented, then followed by the specific modelling details for the alternating navigation/generation and continuously generating/navigating routing methods.

4.3.1 Alternating Navigation and Generation (ANG)

The first algorithm discussed is that picked for the barge system employing a DPS to stay in place and is described earlier in Section 3.4. Some routing algorithm logics corresponding to the one described in Subsection 2.3.5 are described in literature which were referred to model the decision algorithm for navigation [16, 40]. Drawing on the logic and methods used in literature for the types of systems that alternate between energy generation and system navigation, a routing and decision-making algorithm was developed in accordance with the objectives and constraints described in Section 3.4.

Search Algorithm Parameters

The routing algorithm is characterized by certain parameters which determine the extent of the forecasting and accessible area to the system for it to move to. These parameters are described below in Table 13 below.

Table 13: Routing Algorithm parameters for the alternating navigation and generation routing method

Parameter	*Variable*	*Description*
Stationary Operation Time	S	Hours spent in each location when it is reached, during which DPS is employed and turbine is in operation and generating electricity.
Max travel time	T	Maximum number of hours that the system may travel for to reach new optimum.
Travelling Speed	V_b	Speed of travel, assumed constant during travelling sections.
Unsafe Wave Height	W_h	Mean significant wave height deemed unsafe for UFOWT operation or navigation.

The logic associated with the stationary operational time, S, and maximum travel time parameters, T, is used in literature. This is for a moving UFOWT system which generates electricity while moving between different locations but does not consider wave safety in its decisions [16]. A stationary operational time of 48hrs is used in literature, and to evaluate this choice and investigate if a smaller or larger value would be better a wind intermittency analysis on the wind in the North Sea was conducted. The intermittency analysis had the aim of investigating the minimum value of hours for which a system should stay in an area for energy production before it would be more beneficial to evaluate the next location. A few existing wind farm locations were used but no clear pattern was found which could suggest an optimal value for this parameter, so it was decided to rather conduct simulations testing the routing effectiveness with different S values, which is presented in the result chapter.

The maximum travel time, T, was also initially selected based on work found in literature, where a value of 4hrs was used. This value along with the fixed system travelling speed determine the allowable search area in which the system can look for an optimum next location. The travel speed was initially selected to be 20kmh as found in literature [16]. Both these values were investigated by running simulations with varying routing parameter values to see the interactions between.

For the selection of the safe wave height, a value of 6m was found in literature used to study effect of weather on ADOWT evacuation rates in the Japanese sea [40] which also employed 5MW wind turbines except on a farm scale with an interconnected foundation. A significant wave height above 6m is characteristic of a high sea on the Douglas Sea Scale, the full scale is described in Table 14 below.

Table 14: Douglas Sea Scale for classification of Sea States [67]

Degree	*Wave height*	*Sea State*
0	Not measurable	Calm
1	>0.1m	Rippled
2	0.1-0.5m	Smooth
3	0.5-1.25m	Slight
4	1.25-2.5m	Moderate
5	2.5-4m	Rough
6	4-6m	Very rough
7	6-9m	High
8	9-14m	Very high
9	>14m	Phenomenal

Using lower wave heights in the algorithm would result at some point in more downtime or evacuation from certain areas and thus possibly less power yield. This is both from the lost opportunity of generating electricity in a good wind site which may have rough waters but also from the energy expense associated with the forced movement away from the rough seas. For other safe wave values, rough, moderate, and slight sea states were picked as safety limits to see the effect that these would have on the system performance.

Methodology

The routing algorithm was developed in "levels" to add complexities step by step and allow for easy fall back on the previous level in case there were troubleshooting issues. Overall it took approximately 10 levels of iterations to develop the ANG algorithm, which took it from level 1, which simply looked for the maximum wind speed in the entire North Sea at a given hour, to the final level 10 described in detail in the following subsubsection. Some evolutions of levels involved the introduction of new characteristics of the system which were not defined before (for instance, the turbine power rating or the foundation modelling), while other levels were more focused on re-ordering the code to make it more efficient or remove a limitation of the previous level. The main function/improvement of each level of code iteration is described in Table 15 below.

Table 15: Levels of algorithm development iterations and their respective functions and/or improvements from the previous level. Listed are also the main new inputs to the code and the limitations to take note of for future improvements.

LVL	*Function/Improvement*	*Inputs*	*Limitations*
1	Per hour find the optimal wind location with safe waves	Wind and wave data Safe wave limit	No coasts considered No limits on distances between optimums each hour
2	Find the safe wind optimum within a limited search area	Start position Travel speed Coastal areas	Fixed travel speed, assumed the same in every direction Straight trajectories in between points Does not considered unsafe waves on trajectory
3	Calculate the safe optimum for the next S hours rather than single hour	Routing parameter S	Code runs for each hour, making it slow
4	Run the optimum search in timesteps of S hours rather than single hours	-	-
5	Calculate power yield after every movement	Turbine power curve	No energy costs considered yet
6	Refine the grid data depending on desired k-factor	k-factor	-
7	Replaced certain for-loops with vectorized operations	-	-
8	Calculate the travel energy cost of every movement	Foundation characteristics	Assumes constant C_D
9	Use a power estimate to determine the optimum wind location	-	-
10	Consider travel cost in the decision loop for the next optimum location	-	-

This methodology also allowed for two parallel workflows during the thesis project. One workflow involved the development of the routing algorithm from levels 1-4 which involved mostly data processing and algorithm logic development and implementation. In parallel there was the workflow regarding the research of the system design, involving the turbine and foundation characteristics, and as seen in Table 15's third column, these inputs were implemented in the algorithm at levels 5 and 8 respectively.

Decision Loops

A simplified logic flowchart for the ANG algorithm is shown in Figure 35 below which shows the simulation loop that follows the initialization section of the code (certain inputs are already assumed) and precedes the calculation of the entire simulation energy yield and route determination.

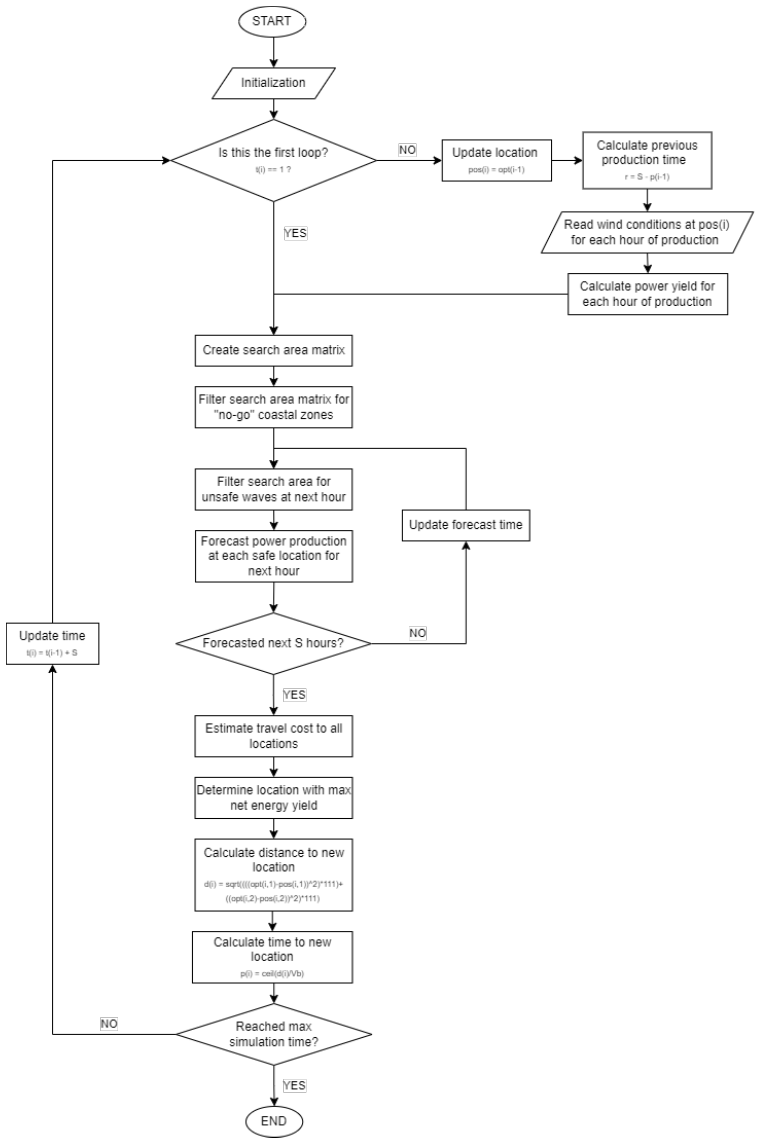

Figure 34: Logic and decision loops of the alternating navigating and generating routing algorithm.

The initialization of the algorithm involves the following inputs:

1. **Wind Turbine Characteristics**
   - Rated power, P_{rated}
   - Rotor Diameter, D
   - Cut-in, cut-out & rated wind speeds, V_{in}, V_{out}, V_{rated}
   - Power coefficient, c_P
   - Air density, ρ_a
   - Drivetrain efficiency, η
   - Total mass, M_{TOT}

2. **Foundation Characteristics**
   - Seawater density, ρ_w
   - Seawater dynamic viscosity, μ
   - Drag coefficient, C_D
   - Characteristic length, L

3. **Routing Parameters**
   - Moving velocity, V_b
   - Stationary production time, S
   - Maximum travel time between optimums, T
   - Safe wave height for navigation, safe_swh
4. **Simulation Parameters**
   - Starting hour, h
   - Starting year, y
   - Starting location, start_pos
   - Simulation duration, sim_hrs
   - Data grid resolution, grain

The wind turbine characteristics are used to build a function for turbine power and thrust with wind speed as an input variable, while the foundation characteristics are used to build a function for drag force. The simulation parameters specify the start and end of the simulation along with the time through the data resolution input. The routing parameters instead define the way the routing algorithm runs, by either extending or shortening certain loops made in the code.

The code is run by first defining a start time, location and specifying the duration for which the simulation shall run. The starting location for the North Sea was picked as a spot just off the coast of Aberdeen port **(57E, -2N)** and an example starting time as 00:00 on January 1st, 2021. The starting location for the western Mediterranean region was selected as **(37N, 0E)**, just off the coast of Spain and near the port of Cartagena. The starting location for the eastern Mediterranean region was selected as **(36N, 15E)** off the coast of Malta and near the port of Valletta.

The simulation is run by making time jumps of S hours, where in increments of S hours, the algorithm reads the past, present and forecasts future weather conditions to determine power produced, power lost and decide on the next location to move to. In the first loop it is assumed that the system has just been dispatched and needs to move to its first production location. The search area is created, by using the routing parameters T and V_b which determine the distance radius around the UFOWT in which the system is allowed to move for the next production location. The search area is essentially a matrix of the dimensions of the data area described in Table 9, Table 10 and Table 11 compromised of 1s and 0s, where 1s are allocated to allowable locations. The position of the UFOWT, upper, lower, rightmost, and leftmost limits of the search area are all converted from degrees to indices with the function *deg2ind*, which makes it possible to allocate values of 1 to these matrix indices, representing squares of sea space.

The search area is then multiplied by the coastal matrix which is another matrix of 1s and 0s representing the navigable and unnavigable regions of the entire data area depending on where there are land/inaccessible regions. The coastal matrix is pre-determined and constant for each region, so it is called as a function *safecoast*, which allows it to also be scaled and interpolated to match the other data matrices used in the code. The size of these matrices is the same and is determined in the initialization step, during which the user may input the desired data-refinement k-factor which interpolates weather data to create a smoother grid.

Once the set of allowable locations to be searched through is determined, a forecast loop is initiated for S hours ahead of time. The code “forecasts” the weather conditions in each location in the search area for each hour and estimates the energy yield that would be reached for those hours. This forecast loop also reads whether there are unsafe waves in this search area, for which movement to these locations is marked as unfavorable and they are not counted in the following calculation for the optimum location. Following the forecasted power yield at all locations in the search area, the travel cost to reach all these locations is estimated and the net sum of the travel cost and energy yield is used to determine the optimal location. The optimum location is simply calculated and seen as the best safe location that yields the maximal net energy yield which is the sum of the forecasted power produced minus the system losses due to the DPS or travel costs. After this is calculated, the location is converted from a set of matrix indices to a set of coordinates by inputting the indexes of this optimal location in the latitude and longitude range of the wind data region. The distance and travel time to this new location are then determined so that these values may be used to update the location and time in the next simulation loop.

Following the first loop and displacement of the UFOWT, the simulation loop re-starts by first updating the time and location determined by the last iteration. The actual power produced and lost are then calculated by reading the weather conditions for the past set of hours during which the system was producing energy. This time amount is the subtraction of the travel time from the S routing parameter.

4.3.2 Continuous Navigation and Generation (CNG)

For the continuous navigation and generation algorithm, a downwind sailing strategy was assumed for the system. Although there are other strategies proposed in literature, such as crosswind in circle or beam reach methods [27] these latter ones become more complex from a stability analysis and control point of view and were left for further developments on this research project.

Working Principle

The primary difference between the alternating and continuously navigating and generating algorithm is the search method for the next route point. Although both systems would ideally want to move to best wind conditions, a continuously moving UFOWT generates electricity even when moving to new locations, so its condition for movement is simply to have a net positive energy yield. For this reason, this algorithm looks for the wind direction in a specified search area and uses wind magnitude to check whether it is beneficial to move. The wind turbine energy conversion modelling must also be altered to account for the experienced relative wind speed instead of the absolute wind speed which runs the ANG system.

Search Algorithm Parameters

The routing parameters used in the continuously navigating and generating algorithm are described in Table 16 below. Since the routing algorithm is more dependent on the naturally occurring wind direction, there are less optimization decisions to be made which justifies the smaller number of parameters.

Table 16: Routing Algorithm parameters for the continuous navigation and generation routing method

Parameter	*Variable*	*Description*
Travelling Speed	V_b	Speed of travel, assumed constant during travelling sections
Unsafe Wave Height	W_h	Mean significant wave height deemed unsafe for UFOWT operation or navigation
Forecast time	F	Number of hours ahead of time for which the route is forecasted so that safety checks and route changes can be made.

The travelling speed parameter has a constant impact on the energy generation of the wind turbine since, as described in Subsection 2.4.2, in a moving UFOWT system the relative wind velocity experienced by the system rather than the actual wind produces electricity. This has an impact on the power curve of the turbine, which is used in the routing algorithm to make certain decisions. Hypothetically a higher travelling speed allows for a quicker change of wind sites, offering advantages in case there are regions with low wind speeds, but it increases the minimum threshold of wind speeds that will allow the system to generate electricity (by approximately the moving vessel speed). This parameter was assumed reflect the methodology of the ANG algorithm but could be adapted to be variable in further improvements of this algorithm.

The unsafe wave height similarly to the ANG is used as a limit on the operation of the UFOWT, differently from the ANG algorithm though, it only stops or starts the system rather than allowing for the algorithm to select alternative routes to avoid unsafe winds, this is due to the assumed downwind strategy which restricts the UFOWT movement to follow the exact wind direction.

The last parameter, forecast time refers to the number of iterations done to look at the upcoming hourly weather conditions from the present. This is used to simulate the likely forecasting function that such a UFOWT system would have, allowing it to make decisions not only on the present conditions but on those that are expected.

Methodology

The same iterative method used to develop the ANG algorithm was used for the CNG but comparatively took less but more lengthy iterations than the CNG algorithm. These four levels are described in Table 17 below, which contains less details than the CNG algorithm evolution since the overlapping coding sections (such as the modelling of some similar components) are not described.

Table 17: Levels of algorithm development iterations and their respective functions and/or improvements from the previous level for the Continuously Navigating and Generating algorithm

LVL	Function/Improvement	Inputs	Limitations
1	Estimate movements assuming downwind movement with the wind	Wind and wave data	Travel speed assumed to be a scaled down value of the wind
2	Estimate energy yield and costs with each movement	Travelling speed Overall system specs	Fixed travelling speed
3	Implement safety limits	Coastal data Max safe wave	-
4	Implement feasibility limits	Adapted cut-in wind speed	-

The workload for the development of this algorithm was concentrated in the first few levels which determined the logic of how the algorithm would read present and forecasted wind directions. Implementation of the system characteristics such as power curves and losses were then similar and accelerated due to the process learned from the development of the ANG algorithm.

Decision Loops

The developed routing algorithm is summarized in the flowchart shown in Figure 35 below. The algorithm allows for any amount of time to be simulated by running iterative loops simulating different hourly weather conditions.

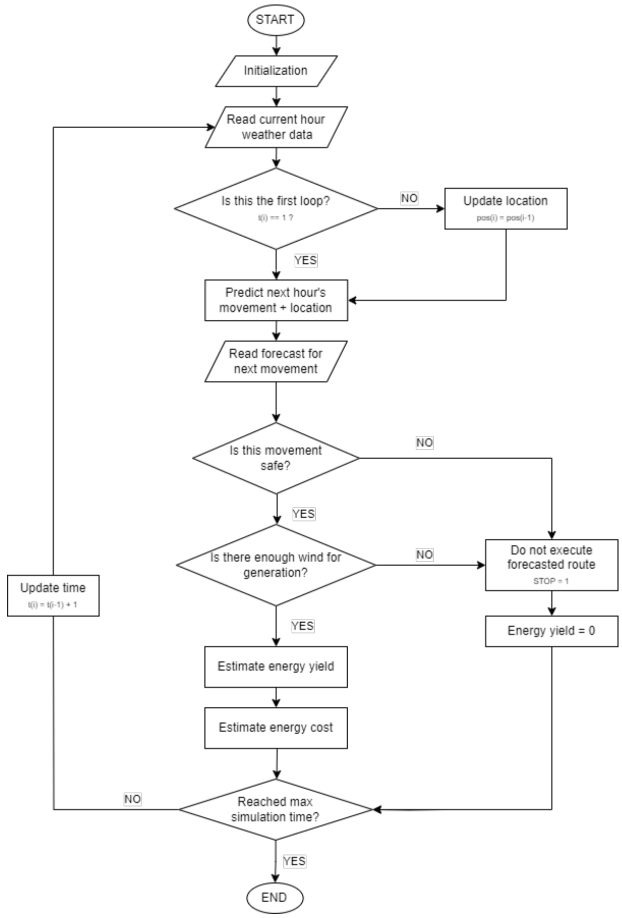

Figure 35: Logic and decision loops of the continuously navigating and generating routing algorithm.

The initialization step of this CGN algorithm is the same as the AGN step described in Section 4.3.1 except the routing parameters are adapted to fit the different working principle and are the following:

3. **Routing Parameters**
   - Moving velocity, V_b
   - Safe wave height for navigation, safe_swh
   - Forecast time, F

The code loop for this algorithm is run each hour to account for changing wind direction conditions. This is obviously an assumption that within an hour the wind direction will remain constant and is made since wind direction data is only available for every hour and not more frequently than that. Each hour the wind and wave data are read and in the first hour the starting location is already known so the weather conditions surrounding the UFOWT system are already known. The wind direction at the starting location is then used to determine the commanded direction of the UFOWT system and given the travel velocity set in the initialization step, the next hour’s movement is calculated, and new coordinates are output. At the new coordinates, the wind and wave data for the next hour is forecasted, to determine whether the forecasted movement is unsafe. If it is safe to make the movement the wind speed is then also assessed to determine whether it is worth operating the system, and if both these conditions are met then the energy yield and cost of this movement are estimated, and the loop is reset. The previously forecasted coordinates become the new starting point and the time is updated by adding one hour.

The mentioned conditions for determining the safety and worthwhileness of a movement include the presence of safe waves (below the max safe wave height specified in the initialization step) and wind speeds above the sum of the travel speed and cut-in wind speed of the turbine (also determined in the initialization step). If these conditions are not met, the system does not move to the next point, so it is assumed that either hydrokinetic turbines, water brakes or other anchoring measures are engaged to avoid this next step. This is done since the system is assumed to produce energy only in downwind conditions so if a downwind direction pushes it to unsafe waters, the best option is to avoid the movement in some way. This is one of the limitations of the model, since it may be more feasible to have the system move in more ways than just downwind, allowing it to still produce some energy, and avoid any energy costs associated with staying still at sea which are not modelled by the CGN algorithm.

The algorithm logic shown in Figure 35 is how the simulation is run when the forecast time parameter F is equal to just one, signifying that the decision moment on whether to proceed or not is based only on the forecast of one hour’s worth of movements. Increasing this value from one increases the complexity of the algorithm since it introduces a for-loop which looks at multiple movements ahead of time. At each forecast step, the forecasted route is used to determine new coordinates, used to read new weather conditions F hours ahead of time, much like the normal algorithm runs. This means that F hours ahead of time are forecasted in terms of route and so the system may make safety decisions multiple hours ahead of time, allowing for a higher safety criterion on the operation. This could further be combined by a forecast in the moving direction of upcoming unsafe wave conditions, so that the algorithm may make decisions on how to avoid harsh weather while still producing energy, or even to evade harsh weather if by chance it encounters it F hours ahead and this harsh weather moves towards the UFOWT system.

5 Results

This chapter presents the results of the simulated routing algorithms for the two UFOWT designs in the three chosen regions of operation. Firstly, the barge system employing the ANG algorithm results are presented in Section 5.1 followed by the results of the trimaran system employing the CNG routing method in Section 5.2. Each design is evaluated in terms of the effects different routing parameters, presented in the previous chapter, have on the system operation and energy yield along with the impact of operation in different climactic regions and seasons. The comparison of the overall performance of the two systems is then made in Section 5.3, this comparison is meant to be quantitative but also qualitative considering the different limitations and assumptions applied to each model.

The results presented for each model are in terms of energy yield, calculated by including only losses related to routing, showing how the energy captured by the wind turbine system compares to the amount of energy consumed by the location changes. Considering the electrical energy yield as is also allows for the moving systems to be compared to a conventional fixed wind turbine in terms of the equivalent hours of operation it would take to accumulate the same amount of electricity. When comparing the two systems, the final hydrogen production is compared which is meant to include all the remaining losses considered in this study, to make a quantitative and qualitative assessment of how both the design and operational method influence the final fuel yield outcome.

5.1 Barge Design

The first model consists of a barge foundation UFOWT described in Section 3.3 which changes locations for energy generation by employing an ANG routing algorithm to lead these location decisions. The turbine system is not generating electricity during movement from one location to the next, and during electricity generation the foundation is kept in place with dynamic positioning systems. The algorithm thus predicts and looks for ideal locations for generation during extensive periods of time.

5.1.1 Routing Algorithm Parameters

The first assessment is made on the routing algorithm parameters that affect the way the algorithm searches for optimums and makes decisions on the alternation between navigation and generation. To do so a fixed period was simulated by individually changing routing parameter values while keeping others fixed. The following simulations are run, displayed in Table 18, using the same simulated weather conditions for the first 30 days of 2021 for all regions.

Table 18: Simulations run to assess the effect of changing routing algorithms for Barge system employing the alternating navigation and generation algorithm.

Simulation / Parameter	*S [hr]*	*T [hr]*	*Vb [km/h]*	*W_h [m]*
Effect of stationary production time	48, 72, 120, 240	4	10	6
Effect of search area size	120	2, 4, 8, 12	10	6
Effect of movement speed	120	4	2.5, 5, 7.5, 10, 12.5	6
Effect of safety limits	120	4	10	1, 2, 4, 6

Each simulation is initialized to start around the same approximate area presented in the previous section. The energy yield is calculated by starting at a zero value at the starting time, simulating a condition in which the UFOWT system was just towed from the coast to the start location and does not yet have fuel stored onboard. This is done for the regions described in Section 3.2 referred to as the North Sea, West Mediterranean, and East Mediterranean regions.

North Sea

The first simulation involved changing the S parameter which defines the time for which the system generates electricity while staying stationary. Figure 36 and Figure 37 show the differences in routes and energy yields for different S parameter scenarios, where each colored line represents the same S value for both figures.

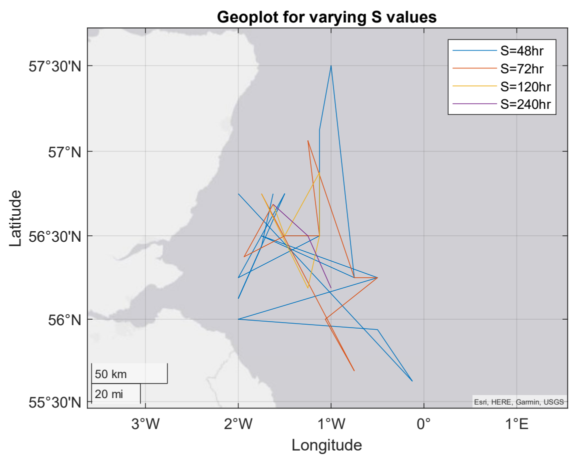

Figure 36: North Sea simulated routes using ANG algorithm and varying the routing parameter S

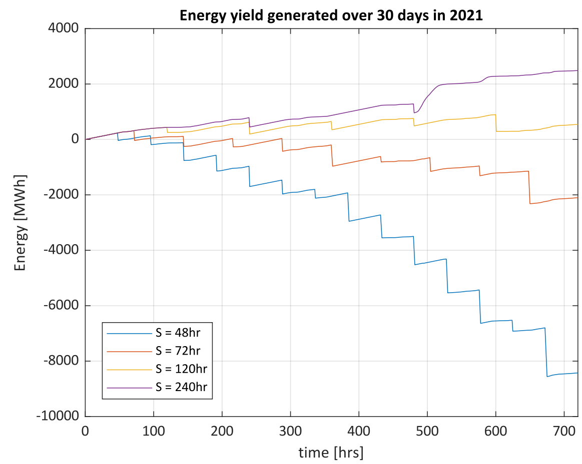

Figure 37: North Sea simulated energy yields using ANG algorithm and varying the routing parameter S

The first direct consequence of incrementing the S parameter from 48hrs to 240hrs is the reduced number of changes in positions in the same 30-day time span. This is seen in the routes displayed but also in the notches in the energy yield plot that are attributed to the energy consumption of the propulsion system every S hours that the UFOWT moves to the next location. In 30 days the UFOWT makes 14 maneuvers when using the 48-hour S value, which then decreases to 9, 5 and 2 maneuvers with the increasing S parameter values.

With an S value approaching a larger number, its seen that the overall energy yield remains positive over the fixed 30-day period for the given system and other routing parameters. For this case, only the S parameters of 120 and 240 hours or equivalent to every 5 or 10 days show to have a feasible operation of the UFOWT for the tested month and wind conditions. Although the 120-hour S simulation shows to have an overall positive energy yield over the 30 days, the energy yield fluctuates around the same value, marking it as a lower limit for this S value for feasibility of this routing algorithm, and so was kept for further simulations. The energy yield of higher S values such as the 240hr one shows an accumulating storage of energy, but in practice also represents a system that makes only 2 movements in the timespan of 30 days and maximum distance of 40km (determined by the multiplication of T and Vb parameters which determine the search area limits at every routing algorithm search iteration). Continuing to increment the value of the S parameter would make the overall UFOWT system appear more like a fixed or moored floating foundation wind turbine from the routing point of view, since it would make fewer movements which would be approximately close together depending on the search area limits. For this reason an S value of 120 hours was kept for the investigation of effects of other routing parameters.

The energy costs for the movement of the system are quantified by the magnitude of the negative notch in the energy yield curves of Figure 37. The simulation of the low S value of 48 hours shows frequent and relatively larger notches than the other curves, due to the algorithm's choice of moving farther than in the other simulations. This decision method may be justified by how the optimum is calculated, which is prioritizing good wind conditions over maintaining net positive energy yield, if this latter was weighted more in the calculation, the overall system would most likely remain fixed when there are non-ideal conditions for movement, creating the same overall effect of the simulations using higher S parameter values. While assessing this consequence of the barge UFOWT system, the alternative of towing was also identified, where a UFOWT system could use other vessels conducting frequent operations in the area to facilitate movement to new wind locations while reducing the amount of energy spent on propulsion. This routing method would obviously depend very much on other factors such as cost and a technical analysis of what type of energy system would be required for such an operation depending on the UFOWT size.

There is to add that the energy expended for movement would still be a cost, if not paid by the UFOWT system by the towing vessel, which may instead be using fossil fuels as an energy source.

Regarding differences in route decisions across the simulations, the change of the S parameter creates the condition that in the first decision loop, each S parameter scenario encounters different weather conditions and forecasts to use for its decision. The 48-hour S simulation runs its first search on January 3rd, while the 240-hour S simulation runs it on January 11th 2021 although they both begin from approximately the same location. In the routing algorithm itself, the optimization for the best energy yield location is also done using S number of hours, suggesting that a few hours or days of bad wind conditions become less relevant for the choice of a location for the high S simulation compared to the low S value simulation that may prioritize staying in the same location or moving farther to reach better wind conditions. Figure 36 shows the differences in route decisions and over 30 days there is little difference between each scenario in terms of prevailing areas of production, and rather all simulations appear to remain in the same area, moving back to previously visited sites. This indicates that the search area radius may be too small to justify movement beyond the area just off the Firth of Forth, which leads into the investigation of routing parameters influencing the search area size.

The next investigated routing parameter is the T parameter, representing the maximum travel time allowed for the UFOWT system between locations. The S parameter was kept fixed at 120 hours, meaning that the search loop was run 5 times to locate 5 optimum locations. The resultant route and energy yield for each simulated scenario are shown in Figure 38 and Figure 39.

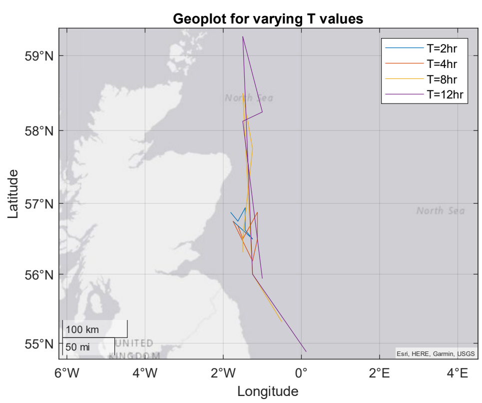

Figure 38: North Sea simulated routes using ANG algorithm and varying the routing parameter T

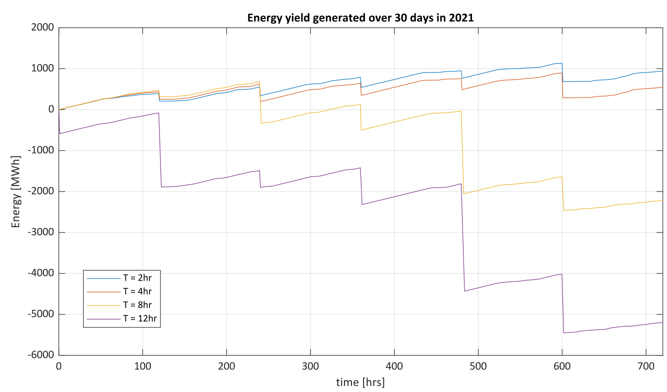

Figure 39: North Sea simulated energy yields using ANG algorithm and varying the routing parameter T

The first direct effect that the increasing T parameter has on the UFOWT system is an increased search area. For the case of 2-hour T value simulation, the UFOWT system was locating optimums within a radius of 20km, compared to the expanded radius seen in the 12-hour radius. The far reached distances travelled during the simulations using 8- and 12-hour values for T show trajectories that would take much more than the defined T value of hours to reach with the fixed 10km/h travelling speed, indicating what must be a mistake in the decision process of the algorithm that could not be tracked down, which likely caused the initial miscalculation of an overall energy cost before the operation of the system begins. Running the simulation multiple times with the same weather data yielded the same route but given the increased travel cost associated with large displacements due to the larger search area, a consistent use of larger search area radius does not show signs to be a sustainable solution in this routing logic. Possible adaptations include alternating use of T values, depending on seasonal changes or state of charge limits placed by the on-board energy storage system. For instance the integration of a condition which if met would trigger the search area to be expanded (e.g. if a certain percentage of the search area has waves above a certain height or the forecasted wind conditions are not promising enough to remain in the fixed search area).

Another way to increase the search area limits is by changing the fixed travel velocity of the system, V_b, as seen in Figure 40 and Figure 41 below. In this instance, the same T value of 4 hours is always used to create a time perimeter on the allowable travel locations, but the different travel speeds mean that this perimeter is different distance wise.

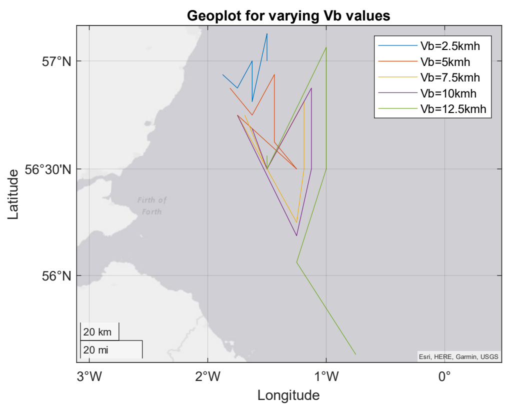

Figure 40: North Sea simulated routes using ANG algorithm and varying the routing parameter V_b

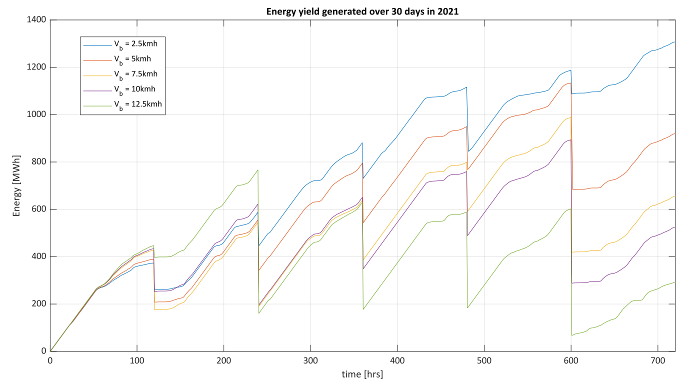

Figure 41: North Sea simulated energy yields using ANG algorithm and varying the routing parameter V_b

The first observable effect of increasing travel velocity on route is the longer distances traveled between each point, likely due to optimums located farther by faster moving simulated UFOWTs. For instance, the second movement of each simulation shows that the highest speed simulation moves the greatest distance in the route map and so has the highest energy expense in the energy yield plot. These large and fast movements cause the faster moving UFOWT simulations to lose most of the energy that was collected in the previous S hours. Together with losses in efficiencies this means that these simulations fluctuating around net zero energy yield are not feasible for fuel production since they would be barely able to supply the energy required for their routing. The possibility of reaching farther from the starting location to the next new wind site is a valuable one for this type of system, but it needs to be combined with an algorithm decision loop which considers the state of charge of the onboard auxiliary energy storage. In practice, it would be likely that the search area may be determined by this state of charge along with the decisions regarding max distance to the next ideal location. Travel speed would be an outcome of this decision process, which would have impact on the time taken to reach the next production location along with the energy expended to reach this next location.

Beyond impacts of changing the S, T and V_b parameters, there's also the impact of changing the safe wave height criterion, W_h, in the routing algorithm. This parameter is critical in the creation of the "safe locations" matrix which changes every hour according to the updated available data on wave conditions. The route and energy yield results for four different simulations are shown in Figure 42 and Figure 43.

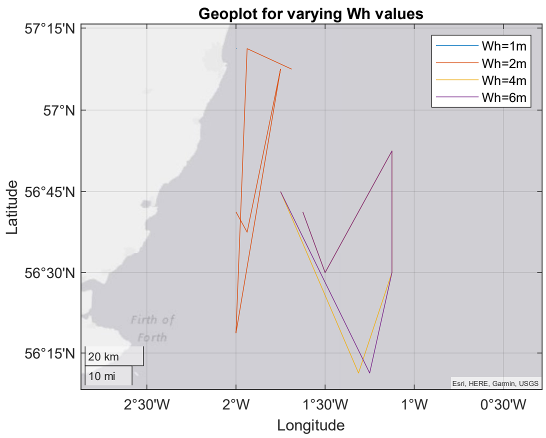

Figure 42: North Sea simulated routes using ANG algorithm and varying the routing parameter W_h

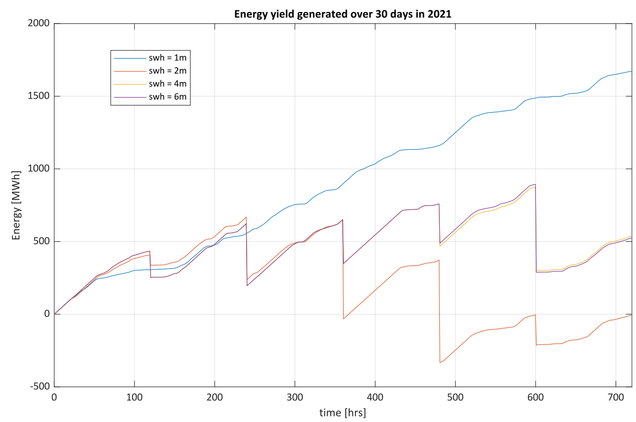

Figure 43: North Sea simulated energy yields using ANG algorithm and varying the routing parameter W_h

The decrease in safe wave height criterion is shown to have a small effect on route and energy yield during the initial decrease from 6m to 4m, indicated by the overlapping energy yield and route lines. This result is dependent on the chosen 30 days of simulated weather and on the location, other periods and/or regions even within the North Sea instead show a greater difference in route decisions and energy yield with the same difference in safe wave limits. Further decreasing this safe limit to 2m instead causes the system to avoid some of the east regions shown in the map and stick closer to the edge of the operational area at 2 degrees west longitude. The energy yield is also influenced by this limit put on the allowable movement locations, since longer distances are travelled by the system to avoid unsafe wave locations, now more frequent as they are defined by waves above 2m. The use of a 1m safe wave criterion instead forces the UFOWT to remain fixed at the starting location since it does not locate feasible or safe alternatives for energy production.

West Mediterranean

For the Mediterranean region, the same parameter variation simulations were run while also keeping the same time duration and period of the initial 30 days of 2021 while using weather data for these specific regions. This was done to also show how different wind sites influence the system operation for the same time period. As discussed in Subsection 3.2.2 the Mediterranean region experiences lower average wind speeds than the North Sea along with lower average significant wave heights, allowing for less limits to be placed on the UFOWT system in terms of safety but also limiting the energy yield. Between the west and east regions of the Mediterranean, the western region shows a more complex region to navigate given the presence of islands in the operation area.

The first routing parameter to be investigated is the stationary operational time, S, using the same values investigated for the North Sea region. The resultant route decisions and energy yields are shown in Figure 44 and Figure 45.

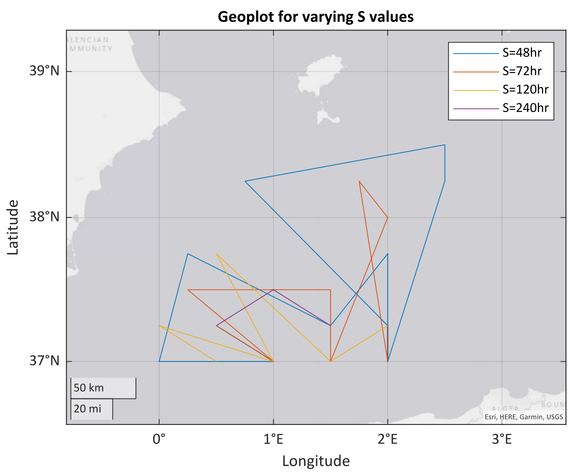

Figure 44: Western Mediterranean simulated routes using ANG algorithm and varying the routing parameter S

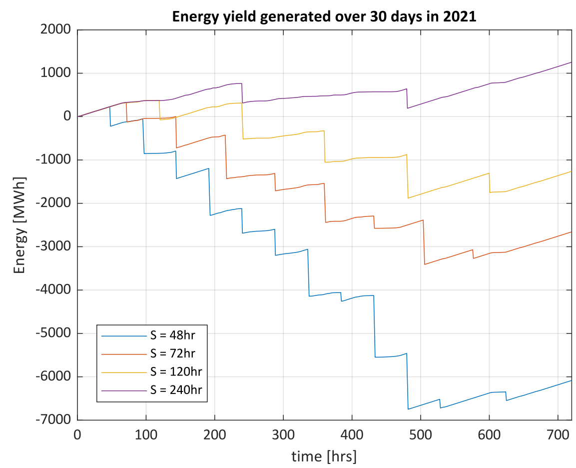

Figure 45: Western Mediterranean simulated energy yields using ANG algorithm and varying the routing parameter S

Since the routing algorithm used is the same in these simulations as the one used in the North Sea ones previously presented, the only differences in terms of route decisions are based on the different weather conditions and different allowable reachable areas due to the region geography. From the energy yield plot, it is seen that the same S value simulations that showed a net positive energy yield over the 30 days (240 and 120 hours) in the North Sea, output a negative value in this region. This is likely due to lower wind speeds present in the West Mediterranean for the same period since the energy yield slopes of the 3rd and 4th location of the 120-hour S value simulation are nearly flat, showing indicating operation below system capacity.

In terms of route distribution, as what occurred in the North Sea, the higher intermittency of movement characterizing the lower S value simulations allows the UFOWT system to use a larger production area. This is advantageous in moments where the other simulations are shown to have lower wind speeds (flatter energy yield increase seen just under 200hrs), but given the routing algorithm logic used, the movements are too far from one another and creating a net energy loss even in this wind site region.

Investigating the effects of changing T values in the West Mediterranean gave similarly misrepresentative routes for higher T values (above 8hrs) as the North Sea results and so were excluded from evaluation. In general the changing effects of search area in the West Mediterranean showed that, for the same 30 days, the region experienced lower wind speeds than the North Sea and the higher costs associated with longer moves due to larger T values were not sustained as strongly by the generation of electricity in this month. For the same 30 days, most of the simulated periods, the West Mediterranean experienced lower wind speeds than the North Sea. The routes taken also show that the ideal wind locations for this period and area seem to be grouped around the lower bound of the area towards the North African coast.

The second method to influence search area was used by adapting the vessel velocities, the effects shown in Figure 46 and Figure 47.

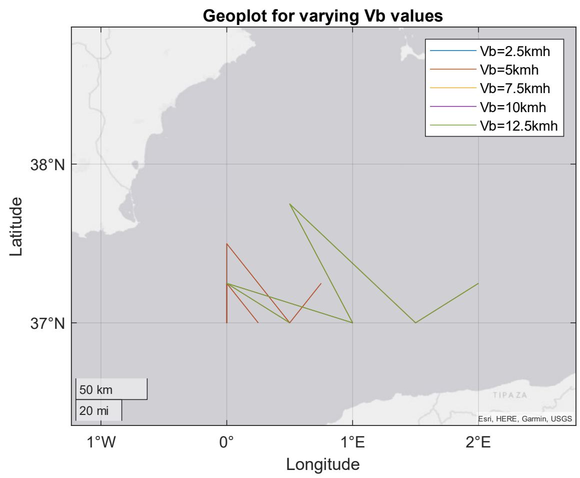

Figure 46: Western Mediterranean simulated routes using ANG algorithm and varying the routing parameter V_b

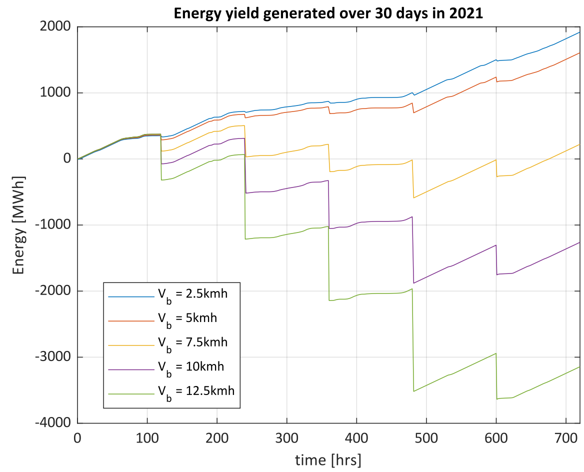

Figure 47: Western Mediterranean simulated energy yields using ANG algorithm and varying the routing parameter V_b

As expected from the results in the North Sea with the same simulation type, the West Mediterranean results show increased drag losses with each UFOWT movement with increasing vessel travel velocity. The routes decided by the system though remain relatively unchanged, since the first two velocity routes all overlap while the last three also overlap in Figure 46. This is expected to be due to other restrictions on the nearby area such as wave heights and coastal limits. The same energy yield at each location but with different energy costs moving to those locations is seen clearly in Figure 47. It can be concluded that in this specific period the increase in movement velocity reaped no benefits by stretching the search area while only increasing the system costs.

The final evaluation for routing parameter effects in the West Mediterranean are shown in Figure 48 and Figure 49 which show the routes and energy yields of different safe wave limits simulations.

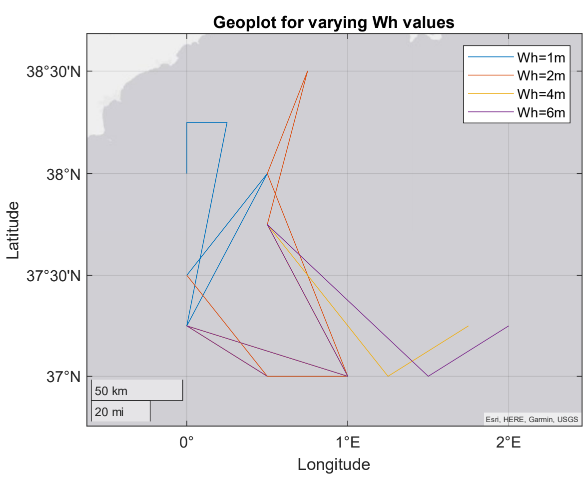

Figure 48: Western Mediterranean simulated routes using ANG algorithm and varying the routing parameter Wh

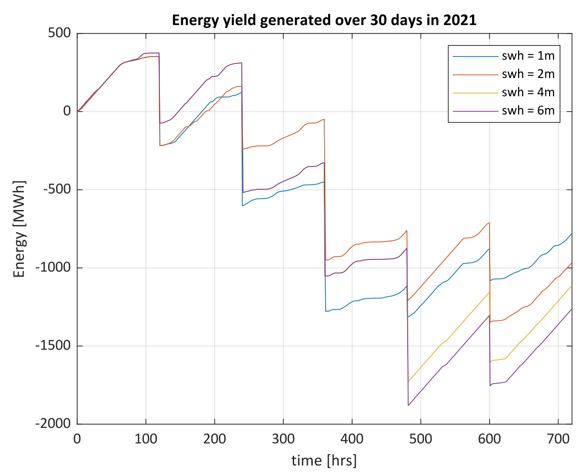

Figure 49: Western Mediterranean simulated energy yields using ANG algorithm and varying the routing parameter W_h

Disregarding the fact that all simulations gave a negative overall energy yield (since the pre-determined fixed routing parameters were used with all regions to allow for a more direct comparison), the change of safe wave height did not give a clear explanation of the effects on system performance. The difference between routes and energy yields was expected to be lower between simulations for the Mediterranean region given the lower average significant wave heights. The route plots for this region did not necessarily confirm this, since the range of operational locations was spread out more than the North Sea simulations, while the energy yield plots showed that the safety limits on the system had different effects each S hours. Looking at the 1m wave height simulation for instance shows that in the first 3 movements, the system made longer movements between location changes, likely due to a more disturbed and changing sea state in that time period and region. Following this, the movements show to become smaller in the following notches shown in the energy yield plot, while also indicating that the last two locations were the most energy producing in this simulation time frame. The higher wave height limit simulations such as the 6m one allowed for better initial wind sites to be chosen in this 30-day range but following this initial lead in energy yield of the higher W_h value simulations, the longer distances travelled during the fourth and fifth movement remove this lead.

While assessing the results of this region, specifically these safe wave limit simulations, it was thought that there could be a specific and possibly predictable factor that would explain the difference in operation and especially energy yield all simulations showed between the first and second half of the month. Following the first week of January in 2021 there was a snowstorm Filomena affecting the Iberian peninsula [74], which could have influenced the simulation results if the wave conditions were on average higher but that does not seem to be the case from the energy yields in the second notch in the energy yield shown in Figure 49 which show that simulations using 4m, 2m and 1m safe wave limits were all producing in the same location.

Overall, the change of location to the West Mediterranean Sea showed a decreased performance for the same UFOWT design developed for the North Sea. This was justified by the reduced wind speeds which caused the same routing algorithm parameters to give worse energy yields. For a 5MW system with a barge foundation the system would either need to operate with less movements to account for the lower energy yield or adapt its design to consider these lower wind speed averages. This could be done by using a wind turbine with a lower rated wind speed or a foundation designed more for navigation that would incur less losses. The Eastern Mediterranean region was also investigated to see how two wind site regions closer together would influence system operation and performance in the same time period.

East Mediterranean

The last region used to test the UFOWT performance is the eastern Mediterranean sea, with starting location just off the coast of Malta. The effects of changing the stationary production time S are shown in Figure 50 and Figure 51 with the routes and energy yields of different simulations.

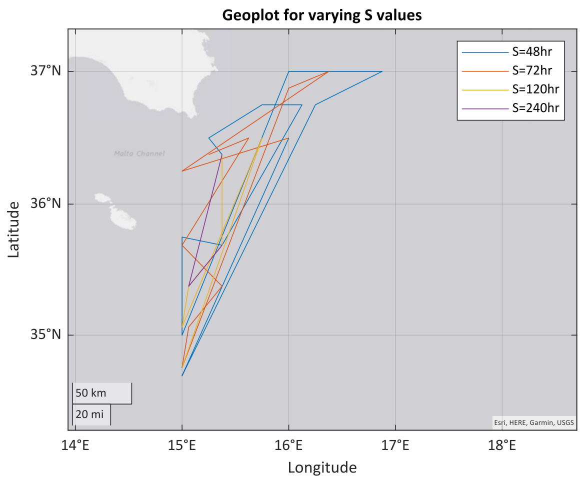

Figure 50: Eastern Mediterranean simulated routes using ANG algorithm and varying the routing parameter S

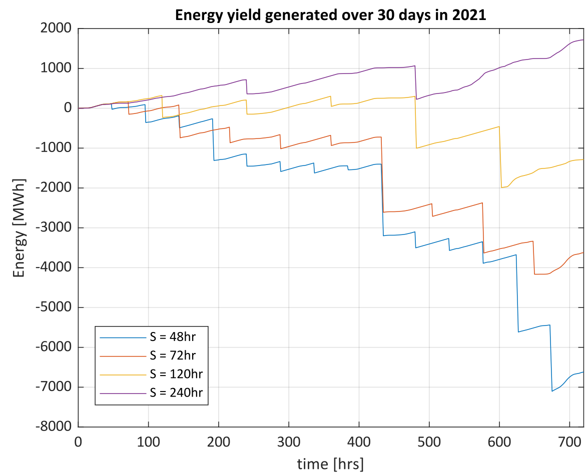

Figure 51: Eastern Mediterranean simulated energy yields using ANG algorithm and varying the routing parameter S

The east Mediterranean showed an interesting range of results during the 30 days of simulations. The overall result of the simulations was like the previous North Sea and West Mediterranean that concluded that values closer to 240 hours for the S parameter would yield a positive net energy accumulation, but there were events during the simulation that drastically impact the energy yield. Around 400-500 hours which would be approximately the 19th day of the month all simulations made the system make a large displacement, which was related to a set of unsafe waves present in the area all the simulated systems were previously frequenting. This reveals a possible limitation of the safety measures of the routing algorithm. In case of a storm which would manifest as a series of future high wind locations, the time between these forecasted high winds and the time it takes for unsafe waves to develop may lead the UFOWT system into dangerous waters that it then needs to travel a long distance to evacuate from.

The second and third parameters to be evaluated were again the maximum travel time parameter T and changing travel velocities (the results of the latter are shown in Figure 52 and Figure 53). Given the same reasoning in the previous region, the results for the changing T values were neglected from the evaluation.

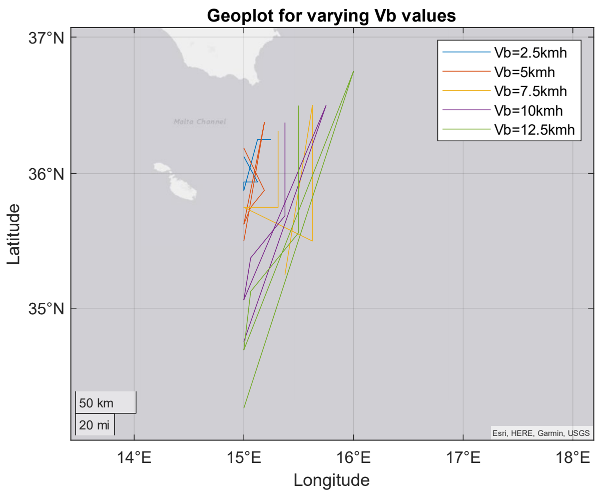

Figure 52: Eastern Mediterranean simulated routes using ANG algorithm and varying the routing parameter Vb

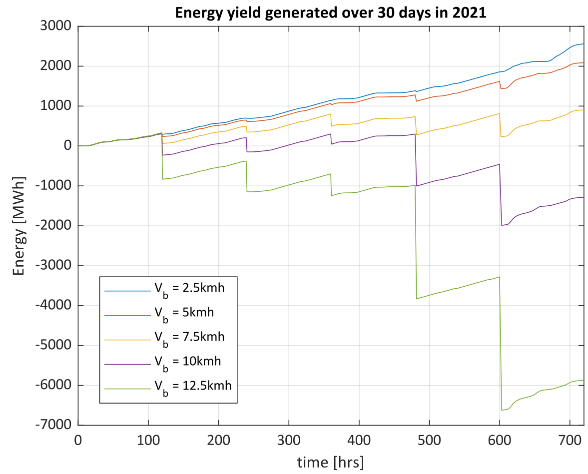

Figure 53: Eastern Mediterranean simulated energy yields using ANG algorithm and varying the routing parameter V_b

The higher T values once again showed unrealistic travel movements, along with the simulation using the higher travel velocities. Only simulations using values of T=2hrs and travel speeds below 7.5kmh while using a T value equal to 4hrs yielded positive energy yield results. The movements of the routes also show that the routing algorithm was limited to the bounds of the area in most decisions, since the chosen locations were both at the 15E coordinate bound and more North near Sicily, indicating that for this month the starting location may not have been an ideal one.

The last routing parameter tested in this region was the safe wave height limit. As was investigated in Chapter 4, the eastern Mediterranean tends to experience higher significant wave heights then the western area, so it was hypothesized that beyond the 30 days tested in January, a low wave height limit in this region may restrict the UFOWT movement more than for the rest of the Mediterranean. The results of the different safe wave limits are shown in Figure 54 and Figure 55.

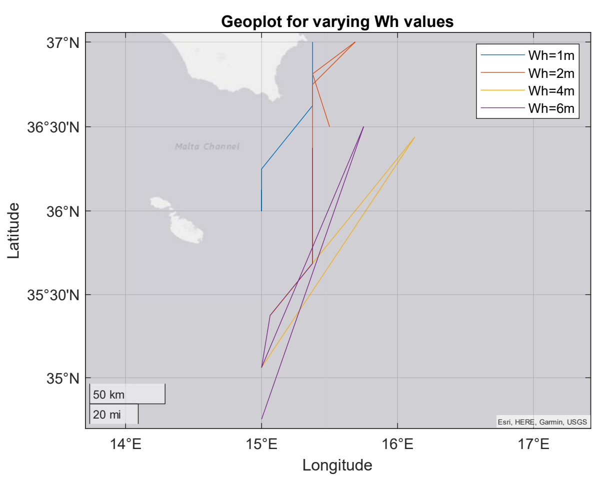

Figure 54: Eastern Mediterranean simulated routes using ANG algorithm and varying the routing parameter W_h

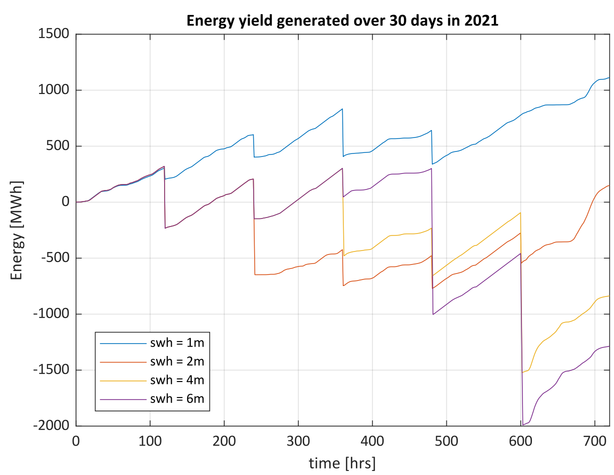

Figure 55: Eastern Mediterranean simulated energy yields using ANG algorithm and varying the routing parameter W_h

The effect of changing the safe wave parameter had the same effect in the Eastern Mediterranean region than in the previously tested areas of limiting UFOWT operation to certain areas, nearer to the starting location for the simulation. A difference with the western Mediterranean region was that the simulations using 1m showed to have a much better energy yield, along with the other simulations compared to the west Mediterranean simulation energy yields which showed to all be negative.

It can be concluded from the result of the first movement decision that storm Filomena which affected the west Mediterranean region after the first week of January did not reach this far into the east of the Mediterranean, since the optimum location is the same for safe wave limits of 2m, 4m and 6m.

5.1.2 Seasonal Effects

From the previous assessment of the effects of changing routing parameters along with other simulations for other time periods, it was concluded that a minimum value of S equal to 120hrs would be required for net positive energy yield, a T value not exceeding 4 hours for the given code set-up (this limit may be changed with certain improvements made to the optimization step, discussed in the improvements section of this report), a lower travel velocity rather than a fast one would reduce the system losses with different movements and finally the safe wave height limit could be reduced to 4m without affecting much of the site availability. This led to further simulations being conducted with fixed parameters S = 120hr, T = 4hr, Vb = 5kmh, Wh = 4m.

The next evaluation of the routing algorithm is the effect that different seasons have on the routing decisions and energy yield of the system across the three different operational areas. The first region in the North Sea is tested with the above routing parameters for simulation times of 3 months at a time, Jan-Mar approximating the winter season, Apr-Jun approximating the spring one, Jul-Sept approximating the summer and Oct-Dec the fall season. Within these simulations no travel back to coast for O&M or refueling is assumed, the aim of the assessment is to see how the energy production and cost amounts differ across seasons along with how the seasons may impact the preferred regions for energy production chosen by the routing algorithm. An initial look at the effect of seasons for instance on operation in 2021 is seen in the energy yield plot in Figure 56 which is associated to the experienced wind speed plot in Figure 57, showing the average wind speeds felt by the UFOWT at each 120hr production interval in the 90 season days.

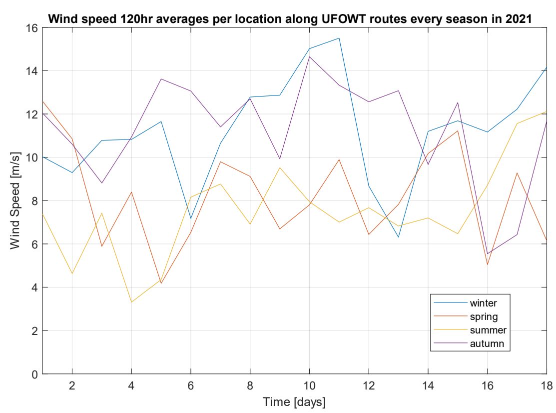

Figure 56: North Sea 2021 average location wind speeds per simulated seasonal routes of the barge system employing the ANG algorithm

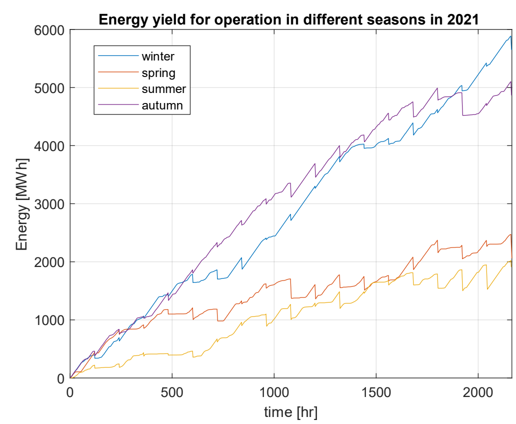

Figure 57: North Sea simulated energy yield in different seasons in 2021 for the barge system employing the ANG routing algorithm

The energy yield plot shows a clear distinction between the winter and autumn months and summer and spring months, due to the lower wind speeds encountered in the warmer months. The same design and routing algorithm performs significantly worse though in the summer period than the winter in this specific year. The time periods in which the energy accumulation reaches plateaus or fluctuates around a mid-point value show an unfeasible system operation given the modelling limitations in the simulation which do not consider expected further energy costs.

When it came to the routes taken, there was no clear distinctive pattern between each seasonal route other than a more frequent relocation to northern locations compared to the starting point during the spring and summer months. This could be explained by the lower wind speeds experienced in the North Sea in the warmer months which would push the UFOWT system farther offshore and North were on average the year-averaged wind speeds are higher.

The yearly seasonal wind averages along with the resultant 3-month simulation energy yield results are shown in Table 19 below, where highlighted in red are the worst-case wind and energy yield conditions while the green show the best encountered wind conditions. These best case and worst cases are used to compare performance with the CNG algorithm and trimaran design in the next subsection. From the simulations, it was seen that the ANG system operated relatively close to the Scottish coast and starting position which let it encounter a ten-year average wind speed of 10.09m/s with an average difference of 2.69m/s between the highest average in winter and lowest average in spring.

Table 19: Yearly seasonal (3 month) encountered wind speed averages and resultant total energy yields during operation for 2012-2021 along with yearly wind averages and total energy yields in last column for each year. The last row shows the average seasonal values for wind speed and energy yield.

Year	*Variable*	*Winter*	*Spring*	*Summer*	*Autumn*	*Average / sum*
2021	Wind [m/s]	11.140	8.214	7.558	11.252	**9.541**
	EY [GWh]	5.656	2.060	1.908	4.865	**14.489**
2020	Wind [m/s]	12.713	8.311	8.489	10.939	**10.113**
	EY [GWh]	6.512	3.077	3.472	5.747	**18.808**
2019	Wind [m/s]	10.955	8.931	9.298	10.971	**10.039**
	EY [GWh]	5.139	3.191	3.571	5.335	**17.236**
2018	Wind [m/s]	10.878	8.728	9.123	11.836	**10.142**
	EY [GWh]	4.836	2.496	3.665	5.539	**16.536**
2017	Wind [m/s]	11.086	9.543	9.169	12.160	**10.489**
	EY [GWh]	5.624	3.232	4.431	6.542	**19.829**
2016	Wind [m/s]	10.903	8.981	9.192	10.307	**9.846**
	EY [GWh]	5.316	3.589	3.161	4.588	**16.655**
2015	Wind [m/s]	12.547	8.712	9.498	11.754	**10.628**
	EY [GWh]	6.146	3.051	4.666	4.702	**18.564**
2014	Wind [m/s]	12.435	8.353	8.302	11.809	**10.225**
	EY [GWh]	5.948	2.835	2.619	5.392	**16.793**
2013	Wind [m/s]	10.095	9.184	8.458	12.638	**10.094**
	EY [GWh]	4.917	3.464	2.678	6.738	**17.797**
2012	Wind [m/s]	11.395	8.324	8.985	10.320	**9.756**
	EY [GWh]	5.375	2.371	3.221	4.463	**15.430**
Average	Wind [m/s]	**11.415**	**8.728**	**8.807**	**11.399**	**10.087**
	EY [GWh]	**5.547**	**2.936**	**3.218**	**5.391**	**16.770**

From the results it’s seen that on average the highest wind speeds are experienced during the winter and autumn months with very little difference between the two seasonal means. The spring period (April-June) has the worst performance that’s on average nearly half of the winter one. This suggests that the operational method should be tweaked or made more flexible for these summer months to minimize energy costs. Additionally, its seen that the highest yield years are characterized by high wind speeds while the worst performing energy yield in 2021 is associated with the worst average wind conditions experienced by the system. This type of correlation is similar to the one experienced by fixed foundation wind turbines whose yield is directly correlated with the wind speed at their operational sites.

Grouping these values by season shows a clearer difference between the variation of wind speeds experienced and outcome energy yields from the UFOWT system, as seen in Figure 58 and Figure 59 below. The colored bars in each season represent the results of the simulated operation from 2012 to 2021 and the wind speeds are those experienced by the moving system at different locations.

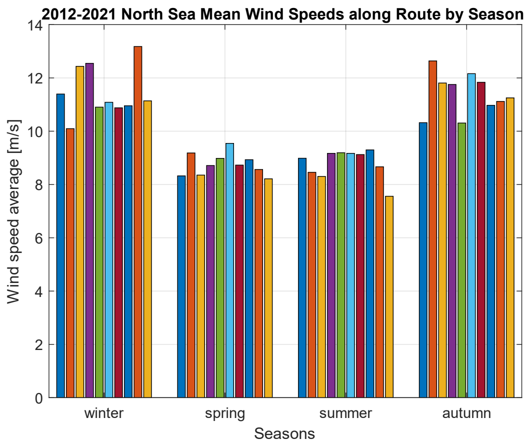

Figure 58: Wind speed averages per season for the years 2012-2021 for simulated routes in the North Sea for the barge system employing ANG routing

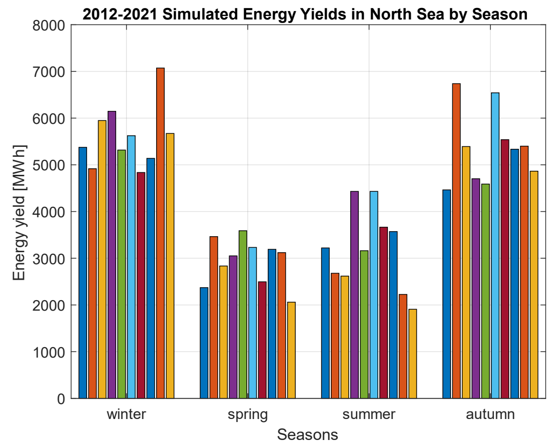

Figure 59: Energy yield averages per season for the years 2012-2021 for simulated routes in the North Sea for the barge system employing ANG routing

Although the difference between wind speeds each season each year are relatively small, the energy yield differences per season are more noticeable. This is due to the energy costs associated with following the "good" wind conditions, which indicates that the routing algorithm as it is set up now puts a higher priority on following ideal wind conditions and not enough on maximizing the energy yield. As was discussed earlier this is due to multiple factors, one may be the choice of maintaining a relatively low S value to simulate moving conditions which causes more frequent sources of losses, or this could also be due to the choice of a larger T and V_b value allowing for too large of a movement range for the UFOWT system without enough limits on energy consumption.

5.2 Trimaran Design

The trimaran foundation UFOWT system employing the ANG algorithm and its performance is presented in this section. Firstly, the power production and costs resulting from the algorithm decisions are presented, showing the direct effect of the chosen algorithm design. Secondly, the effects of changing the travel velocity routing parameter are shown for each geographical area, along with a final evaluation on the effects of seasonal changes on the system.

5.2.1 Routing Decisions

For this second system, the routing decisions are mainly concerning when to activate propulsion systems to navigate and move, and when to remain fixed in place to avoid forecasted route. With ideal winds and safe conditions this system would feasibly constantly move while producing energy. The route taken by the system departing from the starting location at [57N, -2E] and at 00:00 on January 1st, 2021, for 30 days is shown in Figure 60 below, followed by the plot of power generated, lost, and encountered wind speeds in Figure 61.

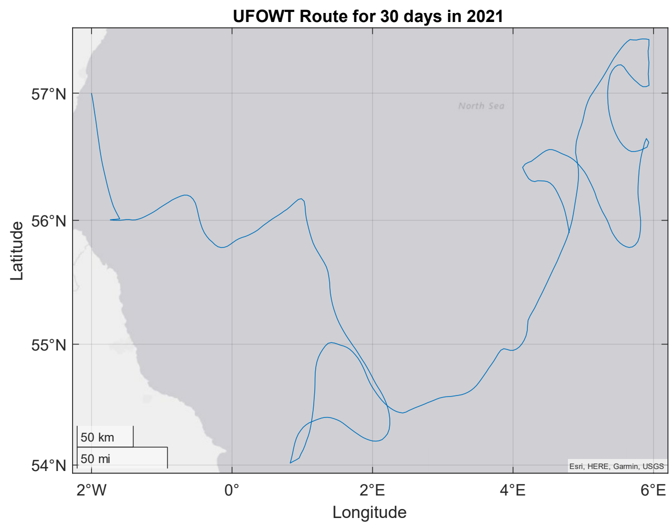

Figure 60: Continuously navigating trimaran UFOWT system route for 30 days at a fixed navigation speed of 5km/h in the North Sea

The route of the trimaran system is very different from the barge system since it is continuously moving and making shorter term decisions (each hour rather than every S hours) on navigation since its objective is to be aligned downwind with the wind for energy production. Smooth route sections show ideal operation, where the system is navigating and generating continuously, while sharp turns or kinks in the route are signs of navigation interruption. As described in Section 4.3 reasons for navigation interruption are linked to reaching out of bounds operational area (such as is seen in Figure near the 54N latitude line or even the 6E longitude line) or unfavorable generating conditions, such as low wind speeds, or possibly incoming unsafe wave conditions.

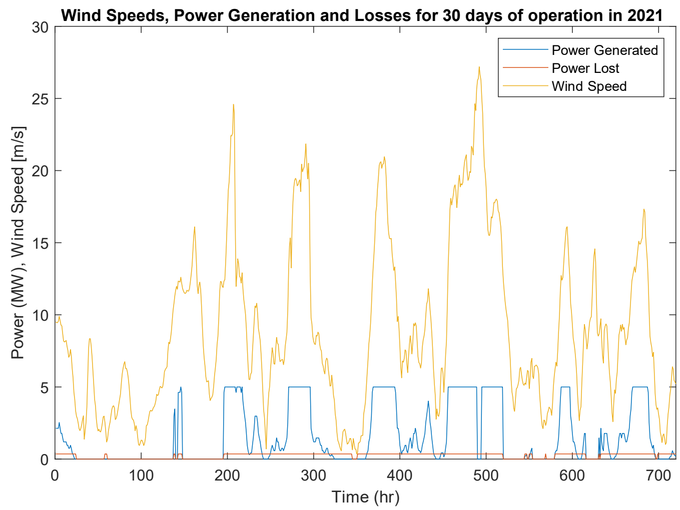

Figure 61: System power, losses, and associated wind speeds for the CNG trimaran system for 30 days of simulated operation in North Sea

The first determinant of power production for the trimaran system is the presence of relative wind speeds above the necessary cut-in speed of the wind turbine. For a system such as one assumed to continuously be aligned downwind with the wind, this necessary wind speed becomes the sum of the turbine cut-in wind speed plus the movement speed of the vessel. For the case of a movement speed of 5km/h used in the simulation that output Figure 61, this minimum wind speed is approximately 4.4m/s. As seen in the figure, in moments where the wind speed drops below just under the 5m/s mark both power production and power losses associated with navigation cease, as seen in the range between 20-100 hours.

In moments where the wind speed is well above the necessary 4.4m/s to make operation feasible, power production and movement can be interrupted by the algorithm in cases where the forecasted route of the algorithm leads it to an unsafe region. The “unsafe” criterion is defined by either presence of coastal areas of regions of waves higher than a specified safe maximum. Hence in the time around 150-200 hours although there is sufficient wind to produce energy and navigate, the system is at standstill.

5.2.2 North Sea

The CGN routing algorithm uses comparatively fewer routing parameters in its design but rather contains many decision loops and forecasts to account for the more frequent decision making of the trimaran system. Regardless, the effects of different travel velocities and safe wave values can be outlined like was done for the barge system. Firstly, the effects of incrementing travel velocity from 2km/h to 7km/h is shown in Figure 62 and Figure 63 below.

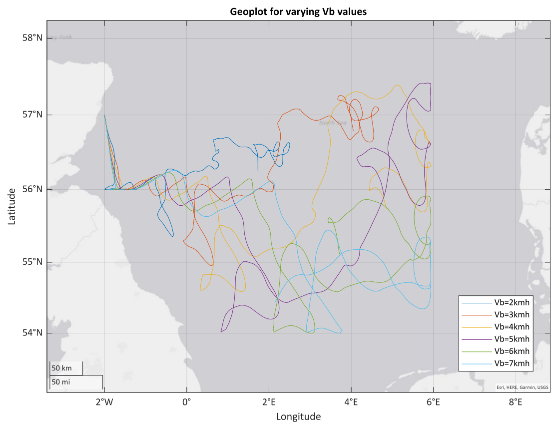

Figure 62: Routes taken by continuously navigating algorithm with same starting location but different navigational speeds

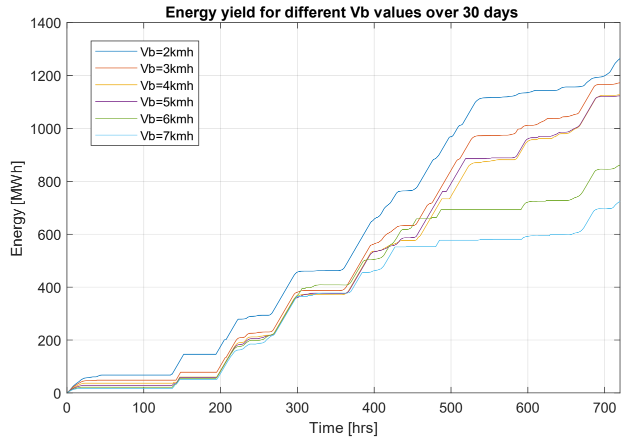

Figure 63: Continuously navigating system energy yields in response to different navigational speeds

The first and expected effect of using a higher travel velocity is a longer route in the same 30 days of simulated time. This is seen in the route outline for the different travel speeds, where the faster simulated systems travel farther east in the North Sea and have a wider range North to South in their trajectory. This has an impact on the system losses as well though, since the UFOWT system is expending more energy to move at a faster speed. Along with this prior factor, the faster movement speed downwind reduces the relative wind speed experienced by the wind turbine, since for example the 2kmh moving system and 7kmh system each experience an 8m/s wind as a 7.44m/s and 6.06m/s inflow of wind respectively. This 1.38m/s difference plays a role specifically in the power curve regions of the cut-in, rated and cut-out wind speed where small variations in this magnitude may determine the operational status of the turbine.

Initially the simulations starting in the same area show the same plateau due to the wind direction pushing them into what would be the unsafe region of the coast of Britain, the plateau height differences are characterized by the differences in energy consumption due to faster/slower travelling in the initial few hours. Overall, the result of this simulation showed that lower travel velocities gave higher energy yields. From closer inspection, during the upward slopes of the energy yield curves, the difference between the different simulations is very little until one of the curves flatten out from what appears to be a moment of standstill operation from having either encountered an operational area boundary or unsafe area. Curves with the same plateaus at a given time show that the simulated UFOWTs possibly encountered the same obstacle (for instance the east-most boundary touched by the 6 and 7 kmh simulations towards the end of the month as seen in the route outlines). From these two observations it could be assumed that changing the movement speed of the UFOWT system has a much greater impact on energy yield since it allows it to reach sites quicker and encounter different wind speeds and/or more unsafe locations. Employing a hybrid routing method with uses low travel speeds when conditions are above a certain “good” threshold for energy production while then using high travel speeds to pass bad weather conditions could be beneficial to reduce the amount of stand-still operation characterizing the higher travel speed simulations.

Another observed difference in the routes of the simulated UFOWTs is the difference in scale of the maneuvers. The changing wind directions across the simulated month can approximately be followed by noticing the same patterns, loops and changes in directions made by all the simulated UFOWTs. Differences in these patterns are due to slight differences in wind direction changes across the North Sea operational area and distance covered by each simulated UFOWT after every wind directional change. This suggests that slower moving systems may indeed require less powerful propulsion systems but will need to account for maneuverability in a smaller space frame than for faster moving systems. As of now the simulations are conducted with changing wind speeds every hour, but realistically there are changing wind directions that occur on a smaller time scale than that.

5.2.3 Mediterranean Regions

Using the same 2021 weather data, an initial look at the difference in operation can be seen in the following two figures showing system route and the associated power generation, losses, and wind speeds. Figure 64 and Figure 65 show the results for the western Mediterranean region while Figure 66 and Figure 67 show the results for the eastern region.

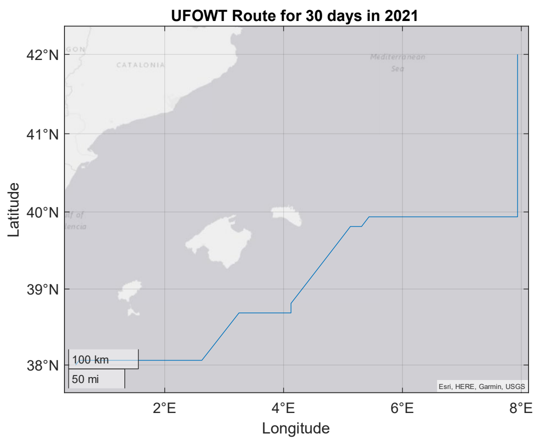

Figure 64: Continuously navigating UFOWT system route for 30 days at a fixed navigation speed of 5kmh in the West Mediterranean

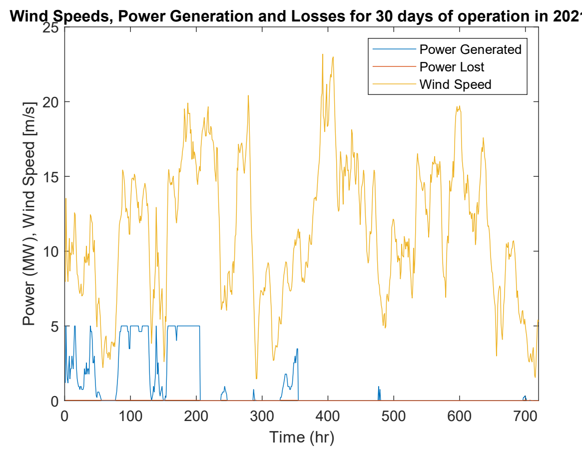

Figure 65: System power, losses, and associated wind speeds for operation of 30 days in the West Mediterranean

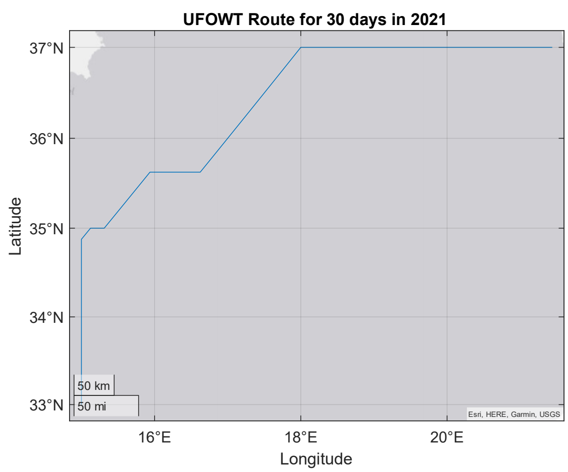

Figure 66: Continuously navigating UFOWT system route for 90 days at a fixed navigation speed of 5kmh in the East Mediterranean

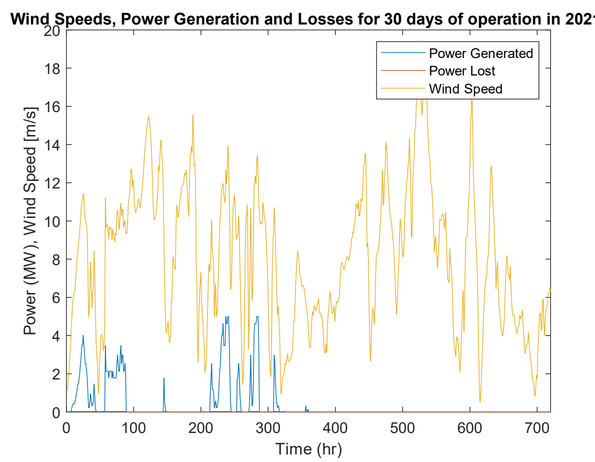

Figure 67: System power, losses, and associated wind speeds for operation of 30 days in the East Mediterranean

Compared to the North Sea the CNG UFOWT system showed very poor performance throughout the year and is apparent from this initial look at the month of January. The system was operation less than 25% of the time in both regions and remaining stuck in an area by the half point of the simulation even with wind speeds above the required minimum amount to allow system operability. The cause of the standstill and lack of energy generation was due to the wind direction pushing the system to the bounds of the operational areas in both simulations. While as discussed, the presence of islands in the western Mediterranean was expected to possibly create such a problem for a system following the wind direction, the eastern Mediterranean results were a surprise since the operational area is much freer from land obstacles.

From this result, the polar histograms were generated for each simulation to determine if certain predominant winds were indeed the cause of the systems ending up stuck at the limit of the operative area. These two polar histograms are shown in Figure 68 and Figure 69 for the west and east Mediterranean regions during the simulations shown in the previous Figures.

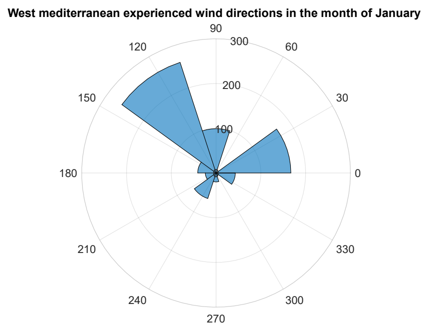

Figure 68: Polar histogram of the wind directions experienced in the month of January in the west Mediterranean region

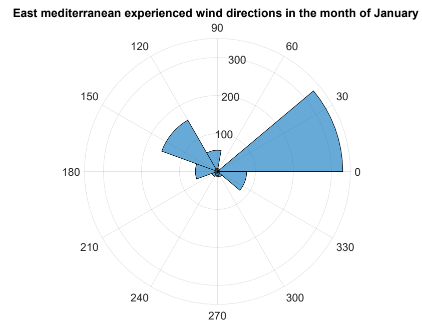

Figure 69: Polar histogram of the wind directions experienced in the month of January in the east Mediterranean region

From the polar histogram its seen that indeed it was the predominant North-Westerly winds in the west Mediterranean and North-Easterly winds in the east Mediterranean that forced the UFOWT systems to the edges of their area of operation which for the developed algorithm meant that they needed to remain fixed in place until the wind changed and allowed for other movements in directions towards the inside of the operational area.

This result highlighted a very significant weakness of the downwind routing method for CNG operation. This standstill issue appears to be most relevant in cases were there would be periods of predominant wind directions in an area, or where there are complex restrictions on the operational area of the UFOWT system. For operation within regions such as the Mediterranean alternative sailing strategies would be needed, also including a direct adaptation of the downwind method which includes an upwind travel when the wind is unfavorable and would serve the purpose of redirecting the UFOWT to its previous starting location. This particular adaptation though would blur the lines defining the differences between the CNG and ANG algorithms.

5.2.4 Seasonal Variations

Similar to the evaluation done in different seasons for the DPS barge system, the effects of seasons in the North Sea were investigated by simulating CNG Trimaran UFOWT operation for 90 days at a time for the four seasons in each year for the years 2012-2021. The single season average wind speeds encountered by the system and resultant energy yields along with the year and season 10-year averages are shown in Table 20.

Table 20: Wind and energy yield averages per season (3 months) along with year averages for trimaran system simulations. Wind speeds in m/s and energy yield in GWh.

Year	*Variable*	*Winter*	*Spring*	*Summer*	*Autumn*	*Average / sum*
2021	Wind [m/s]	10.1504	7.5737	8.0079	11.0049	***9.184225***
	EY [GWh]	3.2329	2.1877	1.7644	3.3863	***10.5713***
2020	Wind [m/s]	13.0311	7.5459	8.1648	10.4738	***9.8039***
	EY [GWh]	2.2454	2.3824	2.6446	1.8386	***9.111***
2019	Wind [m/s]	10.6229	8.5076	8.7466	10.1302	***9.501825***
	EY [GWh]	2.7196	1.7677	2.1175	2.3391	***8.9439***
2018	Wind [m/s]	10.6382	8.4998	8.4351	12.0978	***9.917725***
	EY [GWh]	2.6023	2.2779	0.8942	3.2758	***9.0502***
2017	Wind [m/s]	10.6209	9.1154	8.0573	11.8184	***9.903***
	EY [GWh]	2.5778	2.105	2.3052	3.0122	***10.0002***
2016	Wind [m/s]	10.5538	7.5688	8.1704	8.8126	***8.7764***
	EY [GWh]	3.0064	2.7205	1.3675	2.0357	***9.1301***
2015	Wind [m/s]	11.7484	8.6218	8.547	12.3568	***10.3185***
	EY [GWh]	2.7281	2.1146	2.7523	2.1905	***9.7855***
2014	Wind [m/s]	13.2404	8.2691	7.5708	11.4532	***10.133375***
	EY [GWh]	1.6159	2.1356	2.6013	1.8715	***8.2243***
2013	Wind [m/s]	9.513	9.4869	8.101	11.8685	***9.74235***
	EY [GWh]	2.6229	2.4913	1.7988	2.4544	***9.3674***
2012	Wind [m/s]	10.5223	8.0513	8.9677	10.9262	***9.616875***
	EY [GWh]	2.2422	2.4042	2.4705	3.6985	***10.8154***
Average	Wind [m/s]	**11.064**	**8.324**	**8.277**	**11.094**	***9.690***
	EY [GWh]	**2.559**	**2.259**	**2.072**	**2.610**	***9.500***

An interesting outcome of this analysis was seeing the decoupled trends of energy yield and mean wind speeds, in some seasons, where the “good” wind conditions did not necessarily result in proportionally good energy yield conditions. This was due to the logic implemented in the CNG algorithm, preventing it from moving if certain conditions were met to deem the next movement unsafe or not feasible. The mean wind speeds and resultant energy yields in each season for 10-years (2012-2021) are shown in Figure 70 and Figure 71.

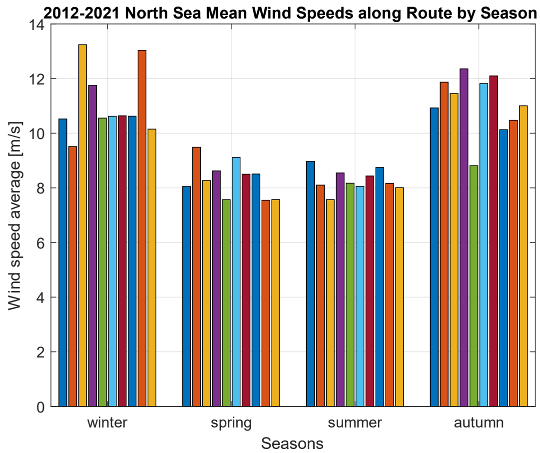

Figure 70: Wind speed averages per season for the years 2012-2021 for simulated routes in the North Sea for the barge system employing CNG routing

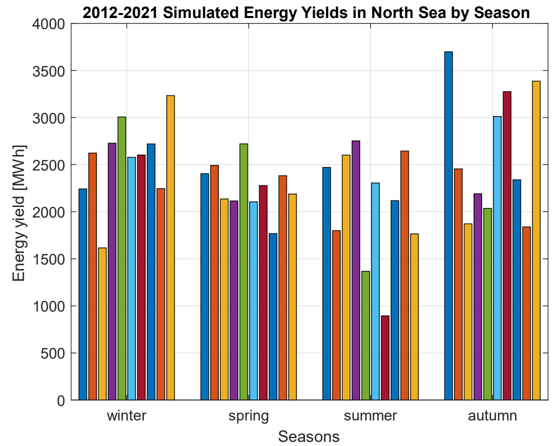

Figure 71: Energy yield averages per season for the years 2012-2021 for simulated routes in the North Sea for the barge system employing CNG routing

A similar result to the AGN algorithm shows that the deviations of wind speed mean values for each speed are much smaller than the deviations of the energy yields for this system. Although the CNG system shows less apparent differences in yields across the seasons during the year, they average out as seen in the table average values and do show a slightly lower energy yield in the spring and summer months. This could be simply due to the system not operating at its ideal conditions and maximum capacity most of the times. The maximum values of yearly seasonal energy yield are shown to be in the 2012 autumn, but this value only barely reaches the highest values seen in the spring and autumn of the ANG algorithm.

On average, given approximately the same route-resultant mean wind speeds experienced by this CNG system, the energy yield was on average significantly lower, 9.5GWh compared to 16.8GWh of the 10-year averaged energy yield of the ANG system. Given that as described in the methodology the energy yields discussed do not yet include some of the costs that are specific to the ANG system (such as the DPS costs), this comparison speaks more to each system's ability to reach good wind sites. A direct comparison can be made when comparing the final fuel production of the two systems, seen in the next section.

5.3 System Comparisons

The barge and trimaran systems are compared to one another in this section in the North Sea in the 10 years between 2012 and 2021. The results of energy yield and hydrogen production are expected to be overestimations since the complete system is not modelled and it would be expected that there are further system losses for regular and prolonged operation, but these values are meant to give an initial guide indicating the differences between designs and modes of operation.

5.3.1 Hydrogen Production Estimates

The difference in performance by season each year for 2012-2021 is summarized in Table 21. The conversion between Nm^3 to kg of hydrogen is done assuming a ratio of $1Nm^3$:0.08988kg [75].

Table 21: Seasonal (3-month averages of) energy yields and hydrogen production estimates for the years 2012-2021 for Barge and Trimaran systems

Year	*Variable*	*Winter*		*Spring*		*Summer*		*Autumn*		*Total*	
	System:	Barge	Trimaran	Barge	Trimaran	Barge	Trimaran	Barge	Trimaran	Barge	Trimaran
2021	EY [GWh]	5.656	3.233	2.060	2.188	1.908	1.764	4.865	3.386	14.489	10.571
	H2 [tonnes]	39.652	22.665	14.442	15.337	13.376	12.370	34.107	23.740	101.577	74.112
2020	EY [GWh]	6.512	2.245	3.077	2.382	3.472	2.645	5.747	1.839	18.808	9.111
	H2 [tonnes]	45.651	15.742	21.571	16.702	24.343	18.540	40.292	12.890	131.857	63.874
2019	EY [GWh]	5.139	2.720	3.191	1.768	3.571	2.118	5.335	2.339	17.236	8.944
	H2 [tonnes]	36.025	19.066	22.371	12.393	25.038	14.845	37.398	16.399	120.832	62.702
2018	EY [GWh]	4.836	2.602	2.496	2.278	3.665	0.894	5.539	3.276	16.536	9.050
	H2 [tonnes]	33.902	18.244	17.497	15.970	25.693	6.269	38.835	22.965	115.927	63.448
2017	EY [GWh]	5.624	2.578	3.232	2.105	4.431	2.305	6.542	3.012	19.829	10.000
	H2 [tonnes]	39.426	18.072	22.658	14.757	31.065	16.161	45.862	21.117	139.011	70.108
2016	EY [GWh]	5.316	3.006	3.589	2.721	3.161	1.368	4.588	2.036	16.655	9.130
	H2 [tonnes]	37.271	21.077	25.161	19.072	22.162	9.587	32.168	14.272	116.762	64.008
2015	EY [GWh]	6.146	2.728	3.051	2.115	4.666	2.752	4.702	2.191	18.564	9.786
	H2 [tonnes]	43.086	19.126	21.388	14.825	32.708	19.295	32.964	15.357	130.146	68.603
2014	EY [GWh]	5.948	1.616	2.835	2.136	2.619	2.601	5.392	1.872	16.793	8.224
	H2 [tonnes]	41.700	11.328	19.872	14.972	18.357	18.237	37.798	13.120	117.727	57.658
2013	EY [GWh]	4.917	2.623	3.464	2.491	2.678	1.799	6.738	2.454	17.797	9.367
	H2 [tonnes]	34.469	18.388	24.281	17.466	18.777	12.611	47.238	17.207	124.766	65.671
2012	EY [GWh]	5.375	2.242	2.371	2.404	3.221	2.471	4.463	3.699	15.430	10.815
	H2 [tonnes]	37.680	15.719	16.622	16.855	22.580	17.320	31.290	25.929	108.172	75.823
Average	EY [GWh]	**5.043**	**2.327**	**2.670**	**2.053**	**3.036**	**1.883**	**4.901**	**2.373**	**15.649**	**8.636**
	H2 [tonnes]	**35.351**	**16.312**	**18.715**	**14.395**	**21.282**	**13.203**	**34.359**	**16.636**	**109.707**	**60.546**

The results show that for these modelled systems, the barge ANG system performs better on average than the trimaran foundation CNG routed UFOWT system in the North Sea. The final energy yields that are 10-year averages for entire years, assuming 90-day dispatch periods during the year with no downtime for maintenance can be evaluated in terms of the equivalent capacify factor of a conventional 5MW turbine. The 15 649MWh average of the barge system is equivalent to 3130hrs of maximum capacity operation or a **capacity factor of 0.36**. Meanwhile the 8 636MWh average of the trimaran system represents 1727hrs of full capacity operation or a **capacity factor of 0.20**. As these are upper limits of capacity factors, expected to decrease with considerations on O&M operations, the UFOWT capacity factors modelled here do not exceed the average factors of the North Sea offshore wind projects which are usually in the 0.4-0.5 range [76].

6 Conclusion

The aim of this research project was to provide a new lens of evaluation on the emerging concept of Unmoored Floating Offshore Wind Turbines (UFOWTs), by focusing on the interaction between design and operational methods of UFOWTs. The literature review component of the project discussed in Chapter 2 allowed for the most prominent routing methods and system designs to be identified and used for the development of the thesis project scope. These designs were then scaled and tailored to industry trends and adapted according to a select set of criteria, shown in Chapter 3, to narrow down the modelling scope to two UFOWT designs each with their own routing method: Both systems using a 5MW HAWT, one with a barge foundation using a alternating navigation and generation routing algorithm and the other with a trimaran foundation for its continuous navigation and generation routing algorithm. The development of the routing decision algorithms for these two systems was described in Chapter 4 and was tested in a set of simulations whose results are presented in Chapter 5. The routing algorithms and UFOWT systems were evaluated in terms of their estimated energy yield and routes decided in the three different geographical locations, the North Sea, West Mediterranean, and East Mediterranean. The overall performance for 10-year averaged simulations was compared to make a final statement on which UFOWT would be better suited as it was modelled in this project, this was the Barge foundation UFOWT system employing the ANG algorithm. Revisiting the initially posed research questions in the introduction chapter, the conclusions of this thesis project are drawn.

1. *How does the routing algorithm logic and decision process of a UFOWT system influence its operation and performance?*

Evident from the development stage of both the ANG and CNG routing algorithms, although both may share the main objective of operating the turbine in a way that energy yield is maximized while keeping the system safe from dangerous conditions, there are different sets of limitations placed on the system as to when it may move or generate electricity. The performance of the chosen UFOWT systems is thus heavily influenced by the routing and control which if too conservative, limits the amount of production time the system experiences.

The ANG algorithm restricted the UFOWT system to wind sites for a fixed amount of time resulting in a pattern of large energy accumulations and consumption by the propulsion system. Under certain circumstances this large fluctuation was feasible although further modelling and development is needed to ensure that the system does not completely extinguish its onboard energy storage at any point of its operation.

The CNG algorithm meanwhile made the UFOWT system more dependent on the wind direction, which meant that in moments where the wind speed wasn't high enough, the wind was directing the system out of bounds or in unsafe waters the system had no alternative but to stop operation. This has a large impact on performance as this system had comparatively more downtime than the ANG system and led it in situations where it could not reroute itself while the wind direction was not changing in the desired direction.

2. *How do the system components and design choices of a UFOWT interact with the routing method?*

Although the two proposed UFOWT systems are the same in terms of exterior design other than their different foundation, the pace, and patterns with which each system converts electricity places restrictions on the other design components on board. An instance of this is the CNG's pattern of frequent alternations between energy production and no production given the experienced different conditions which dictated if operation should occur or not. This type of frequent on and off of the turbine system is problematic for the start-up limitations of the electrolyser onboard. Comparatively the ANG system which aims to keep the times of no production to when it is moving for a few hours at a time, this is much simpler to pair with an electrolyser.

The sizing of the wind turbine also greatly influences the decisions of the routing algorithm, since the forecasting steps within the algorithms predict the power generated by the turbine. Depending on the cut-in and rated speeds of the turbine, these determined which sites would be ideal to move to for the case of the ANG algorithm. Meanwhile the turbine rating had an influence on the CNG algorithm by limiting the moments of energy generation when the relative wind speed was below the cut-in speed. The nature of the CNG routing also meant that it did not follow the optimal wind magnitude sites, which resulted in slightly lower average wind speeds, below the rated wind speed of the 5MW NREL turbine.

The foundation design also directly interacted with the routing algorithm as it was used to make estimations on the energy cost associated with certain routing decisions. For the barge system specifically or foundations that experience a large amount of drag, this limited the operability of the system since it should minimize the energy costs of its decisions. The trimaran foundation comparatively had less of an impact on the energy yield in terms of drag related losses.

3. *How do different climatic and geographic conditions influence the operability of a UFOWT design and routing method?*

The differences in climate across the northern European sea region and southern European one consisted primarily in lower average wind speeds and yearly averaged significant wave heights. The lower wind speeds meant that the systems would overall produce less energy with the same wind turbine, but the lower wave heights also reduced the downtime of the turbines. The initially chosen 5MW turbine design could be downscaled for the operation in the Mediterranean to account for this, especially if used with the CNG system which experienced moments in which it could not operate due to insufficient wind speeds.

Other differences between the investigated regions were the presence of predominant wind directions which heavily impacted the CNG UFOWT system following the downwind direction. For such a mode of operation, operational areas with islands or narrow sections caused the UFOWT system to remain stuck at the boundary of this area until the wind direction changed. Comparatively, the North Sea region offered enough space and wind direction variability to allow for enough directional changes throughout 90 days of operation to limit the number of times it reached the boundary of its operational area.

4. *What barriers and drivers lie ahead for the development of UFOWT concepts beyond their early research phase?*

This last research question was investigated from different points of view throughout the report. In the initial literature review phase, the technological development progress of this technology was researched to identify the research gap that this thesis project could contribute to. It was found that in the recent 10 years UFOWTs have been moving from their TRL 2 to 4. The still present range of designs proposed and studied in literature call for a joint effort across researchers in this realm to share and collaborate on areas that overlap and that can help the overall technology development. In the next phase researching the specifics of onboard components for modelling, it was seen that certain aspects of UFOWT operation set it apart from conventional wind turbines and so put additional requirements and challenges on off the shelf components. Requiring custom designs for UFOWT system components would increase the cost and complexity of the system but may be necessary in some respects. During the modelling section of the report it was found that there are an extensive number of possibilities when it comes to algorithm and routing method development, which should ideally be worked on hand in hand with other researchers looking at systems that will autonomously navigate the seas in the future. This research area is simply not one that is currently involved in the wind energy industry outside of the category of energy ships and thus requires cooperation with other technical disciplines.

In terms of permitting and legislation for this emerging technology, one of the main advantages identified for UFOWTs was the possibility for wind energy to enter a different permitting stream and possibly accelerate the project development phase. Based on Dutch and EU laws, shipping and sailing does not require permitting in the North Sea [77], which if UFOWTs were to fall in this category, would allow them to skip the permitting process. This is an area still left to explore. As an autonomous vessel, UFOWTs would need to follow the emerging laws and regulations currently being developed for other autonomous vessels [53]. Since these regulations are still unknown, this creates an uncertainty on the feasibility of UFOWT deployment in certain areas, potentially creating an additional restriction which could limit the UFOWT reaching wind sites.

Although only briefly mentioned, these UFOWT systems require support during their operation from other vessels and ports for operations involving O&M, towing to and from port and possibly other operations associated with alternative routing methods. These types of cooperations with other parties may act as both a barrier and driver, in terms of increasing the costs of the overall UFOWT project but may also help strengthen the autonomy and feasibility of UFOWT systems operating far offshore.

7 Further Research

This thesis project focused on the overlap between multiple areas affecting UFOWT technologies, which provided insights into the interactions between disciplines but also leaves work to be done to investigate specific aspects more in depth. Two main areas of further research and development were identified and are explained in this chapter, first are the aspects involving the routing algorithms of UFOWTs, detailed in Section 7.1. This section discusses some of the limiting assumptions of the modelled algorithms in this project and how these could be further developed in the future, along with other considerations for UFOWT operation that would need to be implemented in a more complex and realistic routing algorithm. The second area of further research is the one involving the designs of UFOWT themselves and explained in Section 7.2. Here the assumptions and aspects of the UFOWT designs used along with other possible designs not investigated in this project are discussed to give starting points for further research.

7.1 Routing Algorithms

Considering the two routing methods used, each algorithm can be individually developed to consider more constraints and include more complex optimization methods in the decision-making process.

7.1.1 Routing Parameters

For the alternating navigation and generation algorithm, a constant routing parameters S, Vb, T and Wh were used. Development on this would be integrating the decision of the value of some or each of these in the routing algorithm. This could mean that depending on the wind speeds, currents, or onboard state of charge of the auxiliary power system, the range of the search area for the next movement could be adapted by changing the T and Vb values. The S parameter could also be included as a value to be optimized, by suggesting the UFOWT system move only under other constraints.

Thus far when it comes to system safety, the algorithms are not prepared to face storm conditions or quickly changing weather than influences large areas. It was assumed that any evacuation due to large areas of sea experiencing unsafe waves would be communicated and commanded from the coast. As of now the algorithms may detect unsafe waves present various hours of travel ahead but do not have the ability to detect stormy waters and forecast their movement to avoid them. This type of forecast ability could be integrated into the algorithms to make them more independent in their navigation, and this step could be investigated by seeing how it is done currently with vessels.

Further research can also be done on increasing the complexity of the interaction between different routing functions. Given that most UFOWTs are autonomously driven, there is much research to be done also in the development of how this autonomous operation may work. Developing the routing algorithm more in that aspect can involve the addition of more safety precautions, such as collision avoidance, more frequent travel back to port, and possible communication with other vessels at sea [78]. This is a research area is currently being researched and investigated in other fields which are relevant to the autonomous navigation and can be used to further develop the design concept of unmanned UFOWTs.

7.1.2 Navigational Methods

For the trimaran system that is continuously navigating, an interesting multidisciplinary area is found in the overlap of a system that uses the wind to both sail and produce energy. In this thesis project it was assumed that the trimaran system only produces energy when completely aligned downwind and when the wind speeds are higher than the moving vessel speed. Some alternatives to this single navigation methods are the use of crosswind and upwind sailing. Crosswind sailing is used by conventional wind sail vessels while upwind sailing could be achieved by altering the wind turbine design so that it may switch between modes of operation. It would be expected that studying a system which produces energy while sailing crosswind would require adaptations to the wind turbine design or operational method and further considerations into the stability of the foundation used.

7.1.3 Simulating Weather Forecast Inaccuracies

Both algorithms used in this thesis project could be tested in terms of response and resilience to changing weather conditions. In this project, the weather data used in the routing algorithms to make predictive decisions was not altered to reflect the mismatch between a weather forecast and real weather conditions. Using or creating a model which simulates these types of forecast mismatches and testing the routing algorithms with it could give insight into limitations of certain decision loops, operational methods and further strengthen each algorithm. This could involve the use of robust optimization and other stochastic programming methods, which would improve the resilience of the algorithm to changing conditions.

7.2 UFOWT Designs

Since the designs chosen to be studied in this project were based on the formulated decision criteria for design discussed in Chapter 3, another focus for further research could be on proposal of a completely new system design or technical comparison of similar UFOWT designs.

7.2.1 Hydrodynamic Modelling

The assessment of hydrodynamic forces and drag on the foundations of UFOWT in this project were kept very basic, there are some factors that were disregarded such as the changing effect of drag based on the changing draft of the vessel due to increased/reduced fuel weight onboard. The use of other UFOWT foundations or changing design parameters on the barge and trimaran used in this study can be done to further assess the problem of designing the system considering both the hardware and software.

7.2.2 Farm Systems

A further development on this research would be the study of a farm system of UFOWT, which if implemented as individual navigating UFOWTs rather than a connected system would introduce the challenge of synchronizing the navigation algorithm of all individual systems so that the UFOWT farm moves as one, considering the position of the other wind turbines. As mentioned, having such a system would allow also for farm lay-out re-organization depending on wind conditions to avoid wake effects on downstream wind turbines.

7.2.3 Current Modelling

An effect that was not considered in the modelling of both systems is the presence of currents in operation of UFOWTs in open sea areas. This was done due to lack of opensource data that could be coupled with the weather data to calculate real time effects of this. Using real-time data of currents in the simulations could give more insights on the loads applied to the UFOWT system and the realistic impact that currents may have on the system losses. Depending on the region of operation and impact of currents on system, the design or routing method of UFOWTs may need to be altered to consider this impact.

To model the current effects, data would be needed on current velocity, V_c, current direction, α_c, and current load coefficient, C_{xc}, to use in the following equation (19).

$$X_c = \frac{1}{2}\rho V_c^2 C_{xc}(\alpha_c) A_{TS} \quad (19)$$

Where X_C is the drag force acting on the semi-submerged floating structure, A_{TS} is the ship/foundation transverse projected area and ρ being the density of water.

7.2.4 Fuel Conversion

In the scope of this project, industry and research trends were considered for the choice of an alkaline electrolyser to convert the turbine produced electricity for further storage as CGH2. The alkaline electrolyzer modelling was limited by the assumptions that throughout the operating range of 30%-110% of the system power rating the efficiency would remain constant. This could be developed by including a modelling of time and input power specific efficiency calculations to better estimate the hydrogen production at different hours. Furthermore the additionally required systems to operate the electrolyser such as the seawater extraction pump, desalination unit and possible unit used to process the oxygen product could be included in an energy balance model. Associated with the storage of the compressed hydrogen, there are energy costs associated with the compression of the hydrogen which were not considered in this model.

Beyond improving the modelling of alkaline electrolyser and CGH2 storage, further research can be done to consider different types of hydrogen storage, discussed in Section 2.3.4. This could go along with a more in-depth analysis of the operating region-specific energy market, to assess which fuel would be highest in demand by coastal industries.

Other advanced aspects to be considered for fuel conversion onboard a UFOWT systems are consideration of the effects of stabilization for the operation of an electrolyser or other conversion method, temperature effects on conversion (given that the operating range of an alkaline electrolyser is 90±°C) and on storage (for instance on use of cryogenic storage tanks).

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Appendix A

Here are displayed the reviewed articles relating to UFOWTs, ES, ADOWTs and other subcategories of MOWTS and ordered by year.

First Author	Year	Title
Bauer	1969	Faster than the wind (DDFTTW)
Blackford	1985	Optimal Blade Design for Windmill Boats and Vehicles
Blackford	1985	Windmill thrusters comparison of theory and experiment
Bose	1985	Wind turbine drives, test results from the falcon
Bose	1987	Wind turbine for propulsive power generation on Scottish seiner/tawler
Kinoshita	2005	Sailing Wind Farm as Main Energy Resource with Small Load on an Environment
Tsujimoto	2008	Optimum routing of a sailing wind farm
Kim	2009	Wind Power Generation using a parawing, a proposal
Takagi	2009	Improvement in capacity factor and fatigue assessment of VLMOS for wind power generation based on navigation simulation
Takagi	2009	Experimental study on the sailing performance of a VLMOS for wind power plant
Bockmann	2010	Wind Turbine Propulsion of Boats and Ships
Hiramatsu	2010	Sailing Performance of a Very Large Mobile Offshore Structure for Wind Power Plant
Bockmann	2011	Wind Turbine Propulsion of Ships
Yu	2012	wind hydrogen autonomous system with rechargeable battery
Wang	2013	Multibody dynamics of floating wind turbines with large-amplitude motion
Yingjun	2013	Route Optimization Algorithm for Minimum Fuel Consumption of Wind-assisted Ship
Platzer	2014	Renewable hydrogen production using sailing ships
Xu	2016	A novel real-time estimate method of wave drift force for wave feed-forward in dynamic positioning system
Karimi	2017	A multi-objective design optimization approach for floating offshore wind turbine support structures
Pandey	2017	Autonomous Navigation of Catamaran Surface Vessel
Ouchi	2017	Wind hunter concept
Babarit	2018	Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters
Babarit	2019	Energy and econ performance of FARWIND system for sustainable fuel production
Gilloteaux	2019	Preliminary design of a wind driven vessel dedicated to hydrogen production
Jamil	2019	Comparison of the capacity factor of stationary wind turbines and weather-routed energy ships in the far-offshore
Li	2019	A route optimization method based on simulated annealing algorithm for wind-assisted ships
Wang	2019	A Three-Dimensional Dijkstra’s algorithm for multi-objective ship voyage optimization
Annan	2020	Wind Trawler: Operation of wind energy system in far offshore environment
Babarit	2020	Exploitation of far offshore wind with energy ships fleets: updated ship design and cost of energy estimate
Babarit	2020	Exploitation of far offshore wind with energy ships fleets: ship design and performance
Babarit	2020	Exploitation of far offshore wind with energy resource by fleers of energy ships: cost of energy
Beseler	2020	Autonomously driven offshore wind turbine
Bordogna	2020	Aerodynamics of wind assisted ships
Tillig	2020	Design, operation and analysis of wind assisted ships
Alwan	2021	Investigation dynamically positioned floating offshore wind turbine concept

Babarit	2021	Experimental validation energy ship concept for far offshore wind conversion
Orlandi	2021	Meteorological Navigation by Integrating Metocean Forecast Data and Ship Performance Models
Pascual	2021	Wind Energy Ships: Global Analysis of Operability
Platzer	2021	The Green energy ship concept: Chapter 7
Willeke	2021	Concept study of sailing offshore wind turbine
Xu	2021	Novel conceptual design of dynamically positioned wind turbine
Connolly	2022	Modelling power production from unmoored floating wind
Connolly	2022	Optimal power production and operation of unmoored wind and energy ships
Elie	2022	Experiment flettner rotor propulsed ship
Grifol	2022	Ship weather routing system using CMEMS products and A* algorithm
Raisanen	2022	Unmoored: a free-floating wind turbine invention and autonomous open-ocean wind farm concept
Rickert	2022	Conceptual Study and Development of an Autonomously Operating, Sailing Renewable Energy Conversion System
Saenz	2022	Optimal strategies of deployment of far offshore co-located wind-wave energy farms
Connolly	2023	Comparison of optimal power production and operation of unmoored floating offshore wind turbines and energy ships
Annan	2023	Multi-objective optimization for an autonomous unmoored offshore wind energy system substructure