Hydro generation potential on board sailing super yachts

Master Thesis

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Thesis for the degree of MSc in Marine Technology in the specialization of Ship Design

Hydro generation potential on board sailing super yachts

by

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Cover: Perseverance under sail by Baltic (Modified)

Preface

After years of hearing about the increasing need for sustainable advancements in the maritime industry, it gives great satisfaction to contribute something towards this goal. This thesis on the hydro generation potential on board sailing super yachts marks the end of my academic career. Hydro generation is used to limit the emissions produced by sailing superyachts. These yachts are known to have a diesel generator running while sailing to provide the necessary energy, and by generating renewable energy using the propeller when sailing, the diesel generator can be turned off. This is only a small step in the right direction, but all these small steps can be combined into genuine progress for a part of the maritime sector that is not known for its sustainability. The first result of this progress can soon be observed in the design of *Zero*, a fossil fuel-free sailing yacht, and one of the examples used in this thesis.

I want to thank my graduation supervisors Wick and Jaap. Wick for always taking the time to answer my questions when I stood next to his desk again, and Jaap for allowing me to draw my path through this thesis, yet also indicating when it was needed to take a step back and look at the larger picture. Thanks to the entire team at Dykstra Naval Architects, graduating there was an incredible opportunity, and I am grateful for all the insights into the yachting industry and the competitive sailing competition during the lunch break. A special thanks to Mark for sharing your knowledge on the topic. Starting with little knowledge of hydro generation was a challenge, and it would have taken me a lot longer to comprehend the topic without your ideas. Lastly, I want to thank my friends and family for their support throughout these past six years in Delft. I sincerely hope you'll discover new insights and gain a deeper understanding of the topic as you read this report.

Marijn van der Plas
Delft, November 2023

Summary

The yachting industry is growing, and so is the idea of more sustainable yachting. There are many ways to go about lowering emissions on board yachts. This thesis focuses on one of these solutions: hydro generation. Hydro generation is the act of electricity generation by extracting momentum from the water flow underneath a sailing yacht. Hydro generation is an alternative to a standard diesel generator. By harvesting energy from the water flow when under sail, diesel generator use can be limited, reducing overall emissions. Currently, it is not yet possible to quantify the impact of a chosen hydro generation system on the overall design during the early stages of yacht design. To assess the correct balance between the inevitable increase in system weight and size relative to, for example, emission reduction. This thesis provides an in-depth analysis of the possibilities of hydro generation during the early design stages of a sailing yacht, replacing the need for a feasibility study on the topic. This is done in two parts: through a literature analysis that summarizes the limited scientific sources available and by creating a novel design method that builds upon this knowledge.

A hydro generation process has three parts: a turbine that extracts energy from the available momentum, a converter to convert the extracted energy into electricity, and an energy storage system to store the generated electricity. This thesis focuses on the role of the turbine. On a sailing yacht, a propeller will act as the turbine, either the same propeller used for propulsion or a separate propeller designed specifically for hydro generation. The main challenge is the significant difference between propellers optimized for propulsion and propellers optimized for regeneration.

There are six considerations when implementing hydro generation into a yacht's design. The first three concern size. Firstly, the size of the propeller or turbine. The area of the propeller directly influences the amount of power it can extract from the water flow. Secondly, there is the size of the battery, which dictates the required generation frequency. The generated power from hydro generation fluctuates, but with efficient and sufficient energy storage, the yacht can depend for longer durations on hydro generation as its main energy generator. Thirdly, the sail size, there is more benefit from speed as this variable multiplies to the third power in the formula for hydro energy generation. With more power in the sails, a yacht can sail faster, which is more beneficial than sailing often.

The remaining considerations relate to use and indirect design choices. The fourth consideration is the correct energy balance since the amount of power that can be generated is limited. Lowering energy consumption enables reaching goals such as being fully self-sufficient using hydro generation sooner. The fifth consideration is switching from a Fixed Pitch Propeller to a Controllable Pitch Propeller (CPP). This enables optimization in the generation efficiency and energy output. Changing the CPP to a lower power output is beneficial in some situations. The relatively lower decrease in sailing speed will lead to an increase in overall energy output. Lastly, a change can be made in the generation mode. Hydro generation occurs in the first quadrant when an ordinary propeller is used. An efficiency gain occurs by turning the propeller blades 180 degrees, for instance, with a turning thruster. The third quadrant increases maximum output by 30%, relative to the first quadrant, caused by a correct camber in the flow direction, which outweighs the negatives of switching the original trailing edge for the leading edge.

By implementing multiple changes, a multiplier effect can be observed. This means that the overall system efficiency increase of these combined adaptations is more than the sum of the separate individual changes. However, as with all other parts of a yacht design process, improving one part might cause stagnation in another area. It is a balancing act, and the designed method can help. Applying a combination of the design method and manufacturers' details on specific solutions can answer the question of the most effective hydro generation implementation on board a sailing yacht. By providing more insight into hydro generation during an early design stage, when more freedom in the design remains, the bar for the implementation of hydro generation is lowered. Each solution for hydro generation has its limitations. This limitation can be size or weight-related, while other solutions might not meet the customer's expectations. The design method helps with finding these limitations.

This research contributes to understanding hydro generation on board sailing super yachts. The end product of this thesis guides designers in the early stages of the design process in determining the best implementation of a hydro generation solution quickly.

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Nomenclature

Abbreviations

Abbreviation	Definition
CPP	Controllable Pitch Propeller
DNA	Dykstra Naval Architects
DP	Dynamic Positioning
DSYHS	Delft Systemetic Yacht Hull Series
EEDI	Energy Efficiency Design Index
ESS	Energy Storage System
FPP	Fixed Pitch Propeller
GT	Gross Tonnage
GUI	Graphic User Interface
HCPP	Hybrid Controllable Pitch Propeller
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LCoE	Levelised Cost of Energy
PCU	Pitch Control Unit
PPP	Performance Prediction Program
PTI	Power Take In
PTO	Power Take Off
Straflo	Straight flow
TRL	Technology Readiness Level
YETI	Yacht Environmental Transparency Index

Symbols

Symbol	Definition	Unit
A	Area	[m^2]
A_0	Area turbine	[m^2]
A_p	Area propeller	[m^2]
AoA	Angle of attack	[deg]
AWA	Apparent wind angle	[deg]
AWS	Apparent wind speed	[m/s]
$\frac{Ae}{A0}$	Blade area ratio	[-]
b_{wl}	Width water line	[m]
C_d	Drag coefficient	[-]
C_p	Power coefficient	[-]
C_{mast}	Mast height coefficient	[-]
d	Diameter	[m]
F	Force	[kN]
Fr	Froude number	[-]
GT	Gross Tonnage	[-]
g	Gravity	[m/s^2]
h	Head	[m]
J	Advance ratio	[-]
K_t	Thrust coefficient	[-]
K_q	Torque coefficient	[-]

Symbol	Definition	Unit
LCB	Longitudinal center of buoyancy	[m]
LCF	Longitudinal center of floatation	[m]
l	Length	[m]
l_{EM}	Length electic machine	[m]
l_r	Length rotor	[m]
l_{wl}	Length waterline	[m]
n	Rotation speed	[rpm]
n_{sq}	Specific speed	[m/s]
P	Power	[W]
$PiPa$	Prismatic parameter	[-]
$\frac{P}{D}$	Pitch ratio	[-]
p	Pressure	[Pa]
Q	Torque	[kNm]
R	Resistance	[kN]
T	Thrust	[kN]
t	Draft	[m]
TWA	True wind angle	[deg]
TWS	True wind speed	[m/s]
V	Velocity	[m/s]
V_a	Advanced velocity	[m/s]
V_{blade}	Blade velocity	[m/s]
$\dot{V}$	Volumetric flow rate	[m^3/s]
V_s	Ship velocity	[m/s]
v_{water}	Kinematic viscosity water	[m^2/s]
WSA	Wetted surface area	[m^2]
w	Wake	[-]
α	Angle of attack	[deg]
β	Hydrodynamic pitch angle	[deg]
η	Efficiency	[-]
ρ	Density	[kg/m^3]
τ	Shear stress	[N/m^2]
λ	Shape factor	[-]
∇	Volumetric displacement	[-]
#	Number of	[-]
$\angle$	Angle	[deg]

1 Introduction

The yachting industry is growing, and so is the idea of sustainable yachting (Museler, 2016). Sailing yachts could limit emissions from the yachting sector with their ability to transit without using fossil fuels. However, a modern sailing yacht requires electricity for its hotel load and navigation during sailing. This electricity is usually provided by the main engine or a generator that runs on fossil fuels.

Several alternative solutions can provide the electricity required to satisfy the hotel load of a vessel. This graduation thesis focuses on one of these alternatives: hydro generation. Hydro generation is the act of electricity generation by extracting momentum from the water flow underneath a sailing yacht. The implementation of hydro generation serves two purposes: economic and ecological improvement. Installing a hydro generation system limits the use of fuel onboard, decreases fuel costs, and cuts down the emissions generated by the yacht. The addition of hydro generation does come with several difficulties to overcome that are analyzed in this thesis.

The thesis is written in collaboration with Dykstra Naval Architects (DNA), a company with over 50 years of experience in the design, redesign, naval architecture, and marine engineering of classic and modern performance yachts. The company is one of the leaders in transitioning to more sustainable yachting. With a focus on sailing, the company has added several vessels to its portfolio that can generate energy while sailing, using their propulsion systems, such as *Black Pearl* and *Perseverance*. The latest addition to this list is a sailing yacht for *Foundation Zero*, a fossil fuel-free yacht (Leslie-Miller & van Someren, 2022).

1.1. Problem definition and thesis goal

Currently, there are various options and configurations for hydro generation. However, what would perform best on sailing yachts, such as those designed by DNA, is still unclear. Additionally, the knowledge of all separate components required for hydro generation is available, but not how these perform when combined. It is not yet possible to quantify the impact of a chosen hydro generation system on the overall design during the early stages of yacht design. To assess the correct balance between the inevitable increase in system weight and size relative to, for example, emission reduction. The result is a requirement for a feasibility study on hydro generation during every yacht design process. This thesis provides an in-depth analysis of the possibilities of hydro generation during the early design stages of a sailing yacht, replacing the need for a feasibility study on the topic. To allow for this, a novel method is developed, presenting the designer with the opportunity to explore various hydro generation systems quickly.

From an industrial viewpoint, it is interesting to see if all available knowledge can be joined into one place to create a clear overview and limit the need for feasibility studies for each yacht. Additional knowledge on the limitations and possibilities of hydro generation helps with this as well. From a societal perspective, this research can help to reduce the environmental impact of an industry often deemed unethical, partially due to the overall emissions produced. The objective is to report on the possible options and configurations for hydro generation onboard sailing yachts from the perspective of a naval architect. The literature analysis completed for this report combines and summarizes the limited scientific sources available. A design method constructed for this thesis builds upon this knowledge and provides insight into a specific scenario for sailing yachts.

The end product of this thesis guides designers in the early stages of designing a sailing yacht on determining the best implementation of a hydro generation solution. By combining the information from the novel design method with the design requirements set by both the customer and the manufacturer of the hydro generation system, a final system can be selected.

1.2. Research question

The stated thesis goal is summarized in a research question, which is expressed as follows:

How can the most effective hydro generation implementation be selected per individual sailing super yacht, based on the early stage yacht design requirements?

In this thesis, the most effective system is the system that can deliver the most energy, which is a matter of finding the right balance between production and loss. So, the optimal system is a system that provides as much power as possible. Therefore, the word effective in the main research question concerns maximum energy output.

The main research question is supported by several sub-questions that are answered first. The sub-questions aid in building up the knowledge required to answer the main question. A limited amount of literature is written on the actual implementation of hydro generation in yachting. Therefore, only the first and second sub-questions can be answered using literature. The remaining questions are answered using a realistic scenario supported by a design method created for this thesis.

1. What early-stage design elements are significant on board a sailing super yacht, and which of these variables influence the hydro generation system?
2. What solutions for hydro generation are currently applied on sailing yachts, and what solutions can be applied in the future?
   (i) Which existing or proposed propulsion configurations are suitable for hydro generation?
   (ii) What is an alternative approach to hydro generation, both theoretical and manufactured solutions?
3. How can a selection method be formed to determine which hydro generation configuration would suit a specific sailing yacht best?
4. To what extent does the implementation of hydro generation influence sailing yacht design, and which choices indicate the limit of implementation?

A hydro generation process has three parts: a turbine that extracts energy from the available momentum, a converter to convert the extracted energy into electricity, and an energy storage system to store the generated electricity. This thesis focuses on the turbine part due to the significant differences between the available solutions. The design method covers all three parts and includes a complete analysis based on the power and capacity of the other parts but, for instance, not an overview of the specific types of converters. The report aids naval architects in assembling all the information they might require to understand and use the method.

1.3. Thesis report setup

The thesis report is built up to answer the sub-questions chronologically and concludes by answering the main research question. The first and second sub-questions are resolved in chapters two and three. This is accomplished through the analysis of literature written on the topics of yacht design and hydro generation. By analyzing the literature on yacht design and looking into the available options for hydro generation, the focus areas for the novel design method are found. A scenario is introduced and examined using the novel method designed for this thesis for the remaining two sub-questions. Both are explained in chapter four. The following four chapters elaborate on the method's capabilities and how it can be used to examine the scenario. The ninth chapter presents and reviews the findings and the proposed limits by analyzing two sailing yachts and their capabilities using the design method. The report is concluded with a conclusion and discussion.

1.4. Literature search

Chapters two and three start by establishing the basis of energy generation using water and the fundamentals of yacht design. This is followed by the actual application of hydro generation on board yachts.

With limited available literature on hydro generation, the report is supplemented with literature on other relevant topics for hydro generation. The literature search has been accomplished using the following databases: *Scopus*, *WorldCat*, and *Google Scholar*. The search terms to achieve the desired results in the search process were 'Hydro generation or Hybrid propulsion' and 'Yachts or Ships or Vessels', 'Hydro generation', and 'Turbines'. Individual searches were also completed on tidal turbines, the Betz limit, and electric machines. Documents on yacht design were gathered in-house at DNA.

Search criteria were introduced to limit the information to the most relevant parts. These criteria include publication data and document or source type. Literature after 2000 was preferred, and books were mainly used for their source list. The remaining literature was scanned based on keywords and abstracts. Some sources were only used for a very particular part of the text.

2
Theory of yacht design

The design process of a yacht differs per company and even per design. It is an iterative process optimized in cycles, and all choices are correlated. The design stages are divided by the level of detail added. The design process at DNA is summarized in figure 2.1. Each of the four stages has an individual iterative process and is completed before the next stage is started. This report will focus on early-stage design.

The first question of this thesis focuses on the design methodology of yachts and how this design process is influenced when hydro generation is added. The aim is to answer the question: *What early-stage design elements are significant on board a sailing super yacht, and which of these variables influence the hydro generation system?* Firstly, all required definitions are established, followed by an analysis of the early-stage design process. All design elements and considerations influenced by hydro generation are summarized, and the first question is answered in an overview of the chapter.

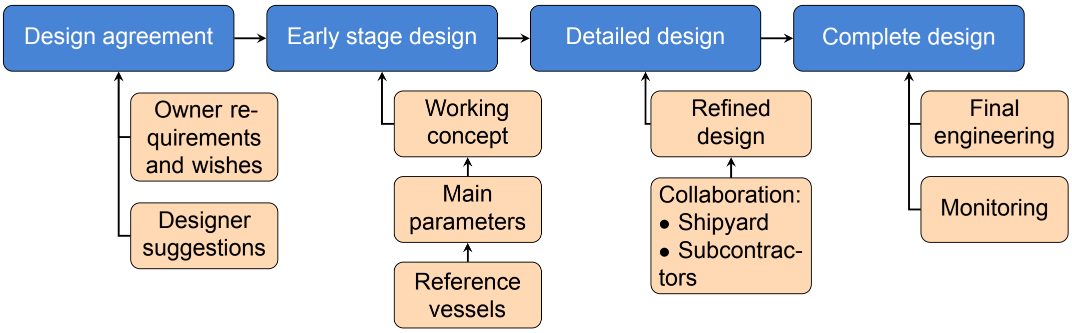


Figure 2.1: Overview of yacht design process

2.1. Yacht definitions

To increase consistency throughout the report, several definitions are established, starting with that of a yacht, particularly a sailing yacht. A sailing yacht is a pleasure craft used for entertainment or sport, designed primarily for sailing, and relies on the wind to propel it through the water. Three decisions on other definitions stand out for this thesis: yacht size, sailing speed, and the coordinate system. These will be elaborated upon in this section. A fourth point of the conversion losses is also discussed.

2.1.1. Size of a super yacht

Hydro generation is becoming a more common option on small pleasure craft. Several companies provide standardized transom-mounted or built-in podded hydro generation systems. This thesis will focus on vessels that require custom solutions, due to their size, instead of these standardized systems.

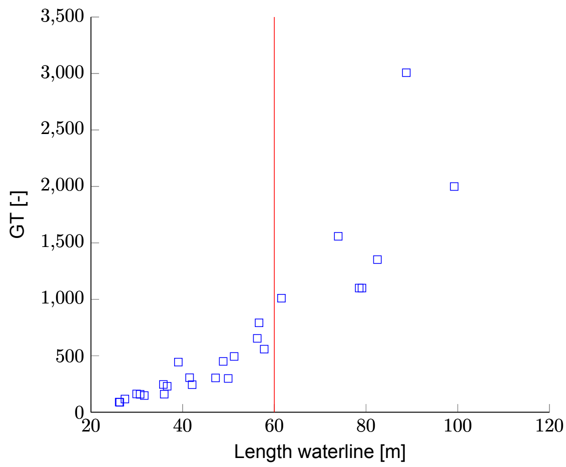
There is not one way of determining whether a yacht is classed as a super yacht. Factors include length, cost, or the requirement for crew. Even within these factors, there is not one set standard. For this thesis, a lower limit is set by the rules of the Offshore Racing Congress (ORC). The ORC states that vessels above 30.48 m are considered super yachts (ORC, 2023). Yachts of this length require a custom solution for hydro generation. There is no maximum size for the super yacht class. Data from DNA shows, as depicted in figure 2.2a, that most yachts designed at DNA are below 60 meters. The variation in yacht parameters increases beyond this point. Therefore, the decision was made to analyze sailing yachts within the 30-to-60-meter range for this thesis.

2.1.2. Required sailing speed

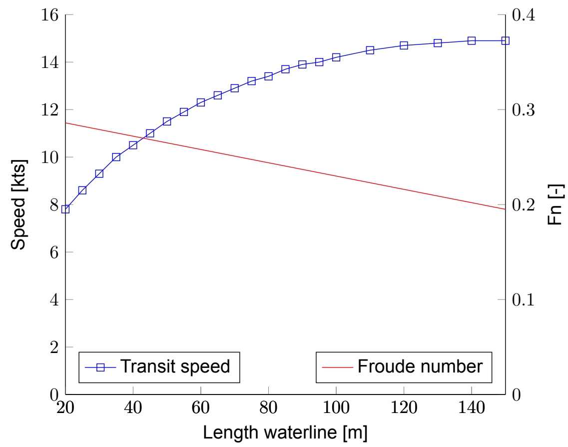
During ocean crossings, the yachts require a certain average speed to complete the passage within the desired transit window. An estimate for this transit speed has been made by DNA using formulas 2.1 and 2.2. These empirical formulas are based on the waterline length and validated using AIS data. If the hydro generation process causes a loss in speed, dropping the average below the required transit speed, the hydro generator is likely switched off. This shows that hydro generation would work best on board sailing yachts that sail often and have sail sets that provide large amounts of power relative to the yacht's length.

$$Fr = 0.3 - 0.1 \cdot \left(\frac{l_{wl}}{150}\right) \tag{2.1}$$

$$V_{transit} = Fr \cdot \frac{\sqrt{g \cdot l_{wl}}}{0.5144} \tag{2.2}$$



(a) Data from a selection of DNA sailing yachts



(b) Estimated cruising speed of yachts

Figure 2.2: Definitions and requirements for yachts

2.1.3. Coordinate system definitions

All calculations in this thesis are made using a ship-based coordinate system with an origin in the center of gravity. The positive x direction is directed to the bow along the yacht's center line. The positive y direction is towards the starboard side. An overview is displayed in figure 2.3.

2.1.4. Conversion losses

The conversion losses are not necessarily a definition. However, the decision was made to remove conversion losses from the equations to improve the clarity. Losses have only been included when explicitly noted. All energy outputs are measured at the connection of the propeller, or turbine, with the shaft. So, without shaft, gearbox, or conversion losses.

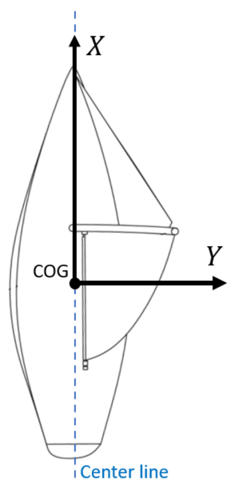


Figure 2.3: Ship-based coordinate system

2.2. Early stage design process

The early stage starts when the general concept of the yacht is complete. In the previous design stage, the intended functionality requirements have been determined. The predominant aspects, such as the number of hulls, styling ideas, and special features, are determined next. Using reference vessels, a first estimation of the main parameters is made. The parameters of interest depend on the design and the yacht's intended functionality. If needed, a feasibility study is performed for any special features. This thesis aims to eliminate the need for a feasibility study on the possibilities of hydro generation during the early design stages.

With the rough outline complete and approved by the owner, the first version of the actual design is made. This is optimized over time but will not receive any significant overhauls. The optimization aims to find a design version that complies with the predefined requirements. Several calculation tools and digital design software are used in the entire design process. However, it also relies heavily on the experience of designers. The early design stage is complete once the design elements, as listed in figure 2.4, are determined and combined into a working concept.

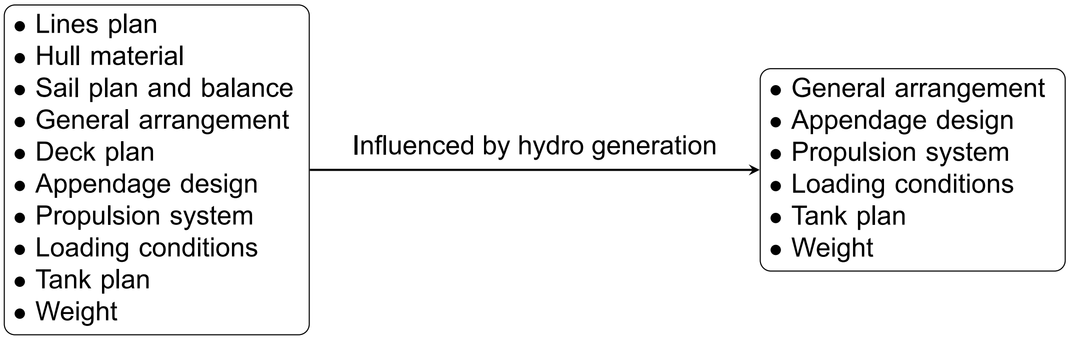


Figure 2.4: List of design elements

This list answers the first question: *What early stage design elements are significant on board a sailing super yacht?* Some of these elements are impacted by the addition of hydro generation. In the table below, an overview is provided, as well as a determination of the level of influence of hydro generation on these elements. Table 2.1 serves as an answer to the question: *Which of these variables can influence the hydro generation system?*

Table 2.1: Summary of influence hydro generation on yacht design

	Level of influence	Nature of influence	Reasoning
General arrangement	1	4	The addition of hydro generation will cost space, especially for batteries.
Appendage design	1	4	The flow around the hull influence hydro generation, appendages might have to change to limit this.
Propulsion system	4	3	The propulsion system needs to a hybrid, this is generally more efficiency but more complex.
Loading conditions	1	1	Less tank fluctuation which results in a smaller range of possible displacements.
Tank plan	3	4	Fuel tanks are replaced with batteries that have a different energy density, and require different locations.
Weight	3	5	The energy density (volumetric and gravimetric) of batteries is lower than the energy density of fuel.

Legend			
Level of influence		Nature of influence	
1	Minor	1	Positive
2		2	
3		3	Neutral
4	Major	4	
-	Not applicable	5	Negative

Overall, as there are more factors to consider, the addition of hydro generation negatively impacts an existing design. Adding systems such as a hydro generation system inevitably leads to a size and weight increase. In the design method, the design elements are considered by examining the dimensions of the hydro generation system parts combined with the weight of the energy storage system. This covers the general arrangement, loading conditions, tank plan, and weight elements. The appendages are considered to remain unchanged, and so is the propulsion system, except for the propeller.

2.3. Design considerations

The design elements are considered the main design drivers. However, other influences on the design should also be considered. These design considerations are not necessarily the main design elements. However, these considerations do play a significant role in the overall design. Five of these design considerations stand out and are discussed in this section: the operational profile, the energy demand, noise, the technology readiness level, and dimensions and cost. These have been selected for the influence that hydro generation has on them. The operational profile and energy demand are also integrated into the design method.

2.3.1. Operational profile

The operational profile (OP) is used during the design process to determine the importance of specific systems and features. The OP is generated by estimating the percentage of the yacht's lifetime that it is on anchor, in port, motoring, or sailing. This can show how often a hydro generation system could be in operation. According to data from the Water-Revolution-Foundation (2021) for the Yacht Environmental Transparency Index (YETI) project, yachts are only underway about 10% of their lifetime. This data set consists of 130 super yachts and is dominated by motor yachts. With the limited available data, it is impossible to prove how often the sailing yachts in this data were under sail. There is also a significant variation in the use of sailing yachts. Depending on the owner and crew, some will sail as often as possible. The use of sails on board sailing yachts mainly depends on the ease of handling the sails and the expertise and number of the crew on board. Lastly, if the schedule is flexible. When enough freedom is offered, the yacht is sailed more often. The presented division in table 2.2 is used as an average operational profile in the rest of this thesis and the design method.

Table 2.2: Operational profile of 130 motor and sailing yachts in a 30 to 120-meter size range (Water-Revolution-Foundation, 2021)

	% of year	Relative % guests	Hours
Harbor	56.0%	3%	4906
At anchor	34.0%	20%	2978
Maneuvering/Loitering/DP	1.5%	45%	131
Cruising slow	7.6%	45%	666
Cruising fast	0.8%	45%	70
Maximum speed	0.1%	100%	9
Total	**100%**	**11%**	**8760**

2.3.2. Energy demand

The energy demand is essential to analyze. It indicates a lower limit for hydro generation before the generator or the main engine is turned off. Estimating the hotel load is difficult during the early stages of the design. And so far, no successful method has been developed that predicts the hotel load. For this thesis, an estimation method has been set up using the graduation thesis on *Modeling the Electric Power Consumption of a Yacht* by van Eesteren Barros (2022). This method is designed on the principle of the Energy Efficiency Design Index (EEDI) groups defined by the International Maritime Organization (IMO). All energy consumers are grouped as shown in figure 2.5. This method is based on data from motor yachts and is adapted for use on sailing yachts, using a multiplication factor based on waterline length.

For a sailing yacht to be self-sufficient during sailing, enough electricity has to be produced to cover the auxiliary and hotel power loads. If the hydro generator can achieve this, in combination with other sustainable sources such as solar, the generator is switched off. A surplus of generated power could even be used to provide propulsion power. Using batteries for peak shaving, the energy in- and output is regulated. For each group van Eesteren Barros (2022) has set up a formula that is applied using either the Gross tonnage (GT), l_{wl}, or Interior space in m^2. These formulas are provided in the appendix A. Group N, covering cargo loads, is left out on board yachts.

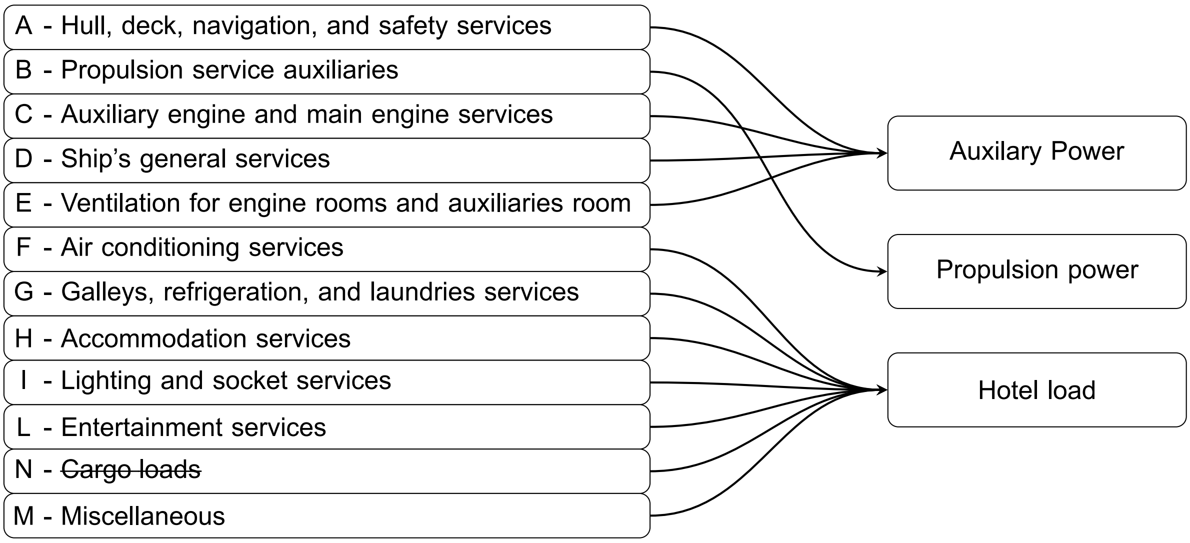


Figure 2.5: EEDI consumer groups

2.3.3. Noise

Noise is a concern with hydro generation. Class rules dictate the requirements for noise levels on board pleasure craft. The accepted levels vary per class society but are in the general range of 45 to 50 decibels for the highest grade cabins (Blanchet, 2000). However, owners might demand a higher level of comfort, so lower noise levels, in certain parts of the yacht. The most dominant source of sound is usually the main engine or, when it occurs, the cavitation of the propeller. During sailing, when the main engine is turned off, the sound produced by hydro generation can dominate. The noise can be created by the generator or the significant load variation on the propeller. If these sounds become too dominant, the hydro generator will be stopped.

An additional concern is cavitation, the process where a phase change from liquid to gas occurs in a fluid due to a change in pressure (Nanda, 2023). Cavitation is unlikely to occur during hydro generation due to the relatively low loads, but not impossible. The best way to limit cavitation noise is to design a propeller with adequate pressure distribution over the blades during propulsion and generation (Casciani-Wood, 2015). An optimal pressure distribution on one propeller can only be reached for either propulsion or generation, not both. When a propeller should be able to achieve both, concessions have to be made. These concessions should not lead to cavitation in either condition.

2.3.4. Technology readiness level

The technology readiness level (TRL) represents the maturity of a technology. As a yacht is a luxury product, most owners demand a product that always operates when they are present. Therefore, if a new technology is added, it should at least be past the prototyping stage. This contradicts the owner's frequent desire for the latest developments on their yachts. To express the maturity level of technology, the concept of seven TRLs was implemented by NASA (Sadin et al., 1989) to show at which stage of development a specific technology is. This list was later updated to nine levels as presented in table 2.3.

2.3.5. Space and cost

Lastly, there are the considerations for space and cost. Space on board yachts comes at a premium, especially on sailing yachts. Therefore, adding a hydro generation system must be done in a space and weight-efficient method. Large sailing yachts are expensive, not only to purchase but also to use and maintain. Adding hydro generation will increase the upfront acquisition costs of a sailing vessel. Hydro generation adds additional systems and the requirement for sufficient battery storage. However, it could decrease operational costs as fuel usage is reduced. Systems on board will have to be maintained, preferably by the crew. This should also be kept in mind when designing complex systems. If a complex system influences the usability of a yacht, the design should probably be simplified.

Table 2.3: NASA technology readiness levels (Banke, 2010)

TRL	NASA implementation
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function or characteristic proof-of-concept
4	Component or breadboard validation in laboratory environment
5	Component or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and ”flight qualified” through test and demonstration (ground or space)
9	Actual system ”flight proven” through successful mission operations

2.4. Overview

The most dominant design elements during the early design stage should be known to set up a design method used in this design stage. A sub-question has been set up to define these elements: *What early-stage design elements are significant on board a sailing super yacht, and which of these variables influence the hydro generation system?* The dominant design elements and how they are influenced are general arrangement, appendage design, propulsion system, loading conditions, tank plan, and weight, as presented in table 2.1.

In the design method, the emphasis is on the dimensions and weight of the hydro generation system parts. This dominates the influence on the general arrangement, loading conditions, tank plan, and weight elements. The appendage design is assumed to remain unchanged. For the propulsion system, only the propeller is changed.

Besides the main design elements, some additional considerations were also studied. These include the OP, energy demand, TRL, noise, and space and cost, which influence the design elements and the overall design. The OP and energy demand are integrated into the design method. The OP provides an insight into the amount of use a hydro generation system theoretically gets. It is hard to predict the absolute amount of use, as this depends on the owner and captain. The average OP of existing yachts is applied during the first design stages to provide an estimate. The energy demand provides the designer with a possible goal to reach with hydro generation. For instance, how much hydro generation is required for an ocean passage without fossil fuels? The energy demand is needed to determine the balance between the used and produced energy. Other design considerations, such as noise and TRL, are more ship or project-specific and are not included in the design method.

3
Theory of hydro generation

Recently, hydro generation has become more popular with the growing trend of hybrid propulsion systems. Each vessel that drives the shaft with an electric motor can theoretically generate electric energy using the propeller and electric motor. There are various options and configurations for hydro generation. However, what would perform best on sailing yachts, such as those designed by DNA, is still unclear.

Additionally, the knowledge of all separate components required for hydro generation is available, but not how these will perform when combined. This chapter will link and summarize the limited scientific sources available and provide insight into the general background on the topic. The objective is to report on the possible options and configurations for hydro generation onboard sailing yachts. First, the physics of hydro generation is generally reviewed, followed by its specific application on ships. Next, possible turbines are examined and compared. The chapter concludes by identifying the possibilities and limitations of hydro generation on board sailing yachts.

3.1. Turbine physics

A hydro turbine is designed to extract energy for a fluid flow. The general formula for turbine power is presented in 3.1. This formula includes the turbine's efficiency and flow power, which can be rewritten to pressure and volumetric flow rate. The efficiency indicates how well the turbine converts energy from the incoming fluid and accounts for all losses like heat or friction. In this formula, the turbine is the entire system, and the output would be all the available usable energy. Figure 3.1 visualizes this complete system as the *Turbine system* that generates an output of $P_{turbine}$.

$$P_{turbine} = \eta_{turbine} \cdot P_{flow} = \eta_{turbine} \cdot p \cdot \dot{V} \tag{3.1}$$

For this thesis, the area of interest is the propeller itself, so the smaller *propeller system* indicated in figure 3.1. To evaluate the actual performance of a propeller and eliminate the losses from the equation, the efficiency is replaced with the power coefficient C_p. The calculated power $P_{extracted}$ is the power at the connection point of the propeller and the shaft. C_p represents the ratio of the actual power output of the turbine to the maximum possible power output that the turbine could theoretically achieve and varies between 0 and 1.

$$C_p = \frac{P_{extracted}}{P_{flow}} = \frac{P_{extracted}}{\frac{1}{2} \cdot \rho \cdot V_a^3 \cdot A_0} \tag{3.2}$$

$$P_{extracted} = C_p \cdot P_{flow} = C_p \cdot \frac{1}{2} \cdot \rho \cdot V_a^3 \cdot A_0 \tag{3.3}$$

A turbine cannot achieve a power coefficient of 100% as this would completely stop the flow through the turbine. For a turbine in open flow, there is a theoretical limit to the amount of kinetic energy that can be extracted. The Lanchester-Betz-Joukovsky limit (Kuik, 2007) depicts the loss-free power efficiency parameter that flows through the area of the turbine. Because the kinetic energy in the fluid through the turbine is reduced, the flow velocity is also reduced. This means that the power coefficient cannot reach the ultimate value of 1. The more energy is removed from the fluid, the more velocity reduction occurs.

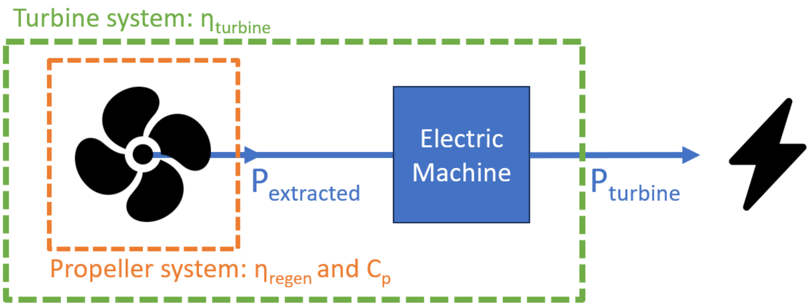


Figure 3.1: System definition for hydro generation systems

The theoretical limit of the power efficiency in open water is mathematically determined at $C_p = \frac{16}{27}$ (Betz, 1920). As this limit is loss-free, mechanical and electrical efficiency are 100%, and the turbine's achieved efficiency is lower than the theoretical limit. An overview of various turbines is provided in 3.2. The theory is based on an undefined fluid and thus applied to hydro turbines.

This definition excludes drag and is thus not ideal for defining efficiency on a moving object, such as a sailing yacht. Including drag is essential as it directly influences the undisturbed flow velocity and the general performance of a hydro generator. The regeneration efficiency is determined using the drag, so resistance, as shown in formula 3.4. The balance between this efficiency and the power coefficient is provided in formula 3.5. Here, η_{regen} is defined as the power harvested at the cost of a sailing speed reduction for the yacht. So, the highest efficiency is reached when turbine output is high compared to low-speed losses. Using the two variables, η in 3.4 for the efficiency regarding loss, and C_p in 3.2 for the energy input, future calculations can be performed dimensionless. This means that both can be used in computations for any speed.

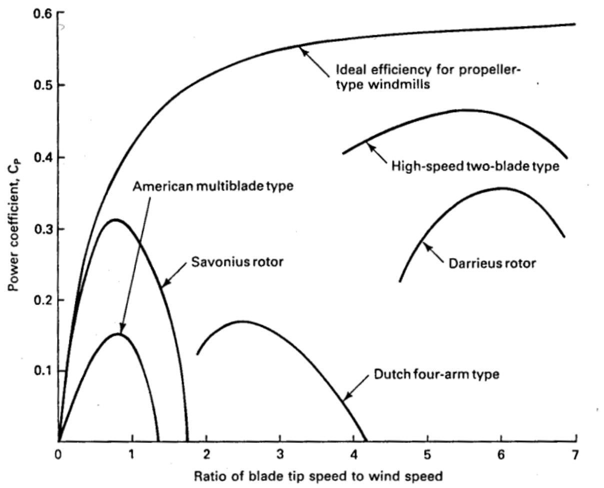


Figure 3.2: C_p vs tip ratio curves for various turbine configurations (Johnson, 2016)

$$\eta_{regen} = \frac{P_{extracted}}{T \cdot V_a} \tag{3.4}$$

$$C_p = \eta_{regen} \cdot C_T \tag{3.5}$$

3.2. Types of turbines

During the 19th century, the first modern types of turbines were developed. The three main types of hydraulic turbines are the Pelton, Francis, and axial turbines. Axial turbines are divided into subgroups such as Kaplan and bulb turbines. Since the invention of these turbines, the development has not stopped. But the working principles and physics have not changed since then (Drtina & Sallaberger, 1999). There are two groups of turbines: impulse turbines that operate on just kinetic energy and reaction turbines that operate on kinetic and pressure energy combined. The turbines are split further using criteria such as shaft orientation, specific speed, head, type of regulations, and design concepts. As the working principle for each turbine varies, they each operate in different regimes. Figure 3.3 shows the three main types of turbines and their operating range based on the head and the specific speed at which they operate. This speed is based on the formula 3.6 (Krzemianowski & Steller, 2021).

$$n_{sq} = \frac{n \cdot V_{flow}^{0.5}}{h^{0.75}} \tag{3.6}$$

Using the criteria and the operating regime, a first estimate is formed to identify which turbine works best on board a sailing yacht. The pressure on the turbine is calculated using a linearized Bernoulli equation. The hydro turbine is placed just underneath the hull, likely as the original or an additional propeller. There is no difference in height for the in and outflow of the turbine, so the estimate is purely based on the dynamic pressure head, and the potential terms are eliminated. This pressure head is rewritten as an actual head in meters. This way, it can be presented in figure 3.3. As such, it follows that formulas 3.7 for the pressure and 3.8 for the pressure head in meters are applied.

$$p_{total} = p_{dynamic} = \frac{1}{2} \cdot \rho \cdot V^2 \tag{3.7}$$

$$h_{pressure} = \frac{p}{\rho \cdot g} \tag{3.8}$$

For a small sailing yacht (under 20 meters) that sails at 8 knots, the pressure head would be 0.9 meters. For a large sailing yacht that sails at 16 knots, the pressure head would be 3.5 meters. Both lines are presented in figure 3.3. From these lines, it becomes apparent that the turbine on board a sailing yacht will likely be an axial turbine due to the relatively low-pressure head. Also, the number of blades on a yacht's propellers is within the range of the number of runner vanes on axial turbines (Drtina & Sallaberger, 1999). In this section, the axial turbines are examined. It is not impossible to increase pressure, for instance, by using nozzles. Therefore, all three turbine types are evaluated in an overview.

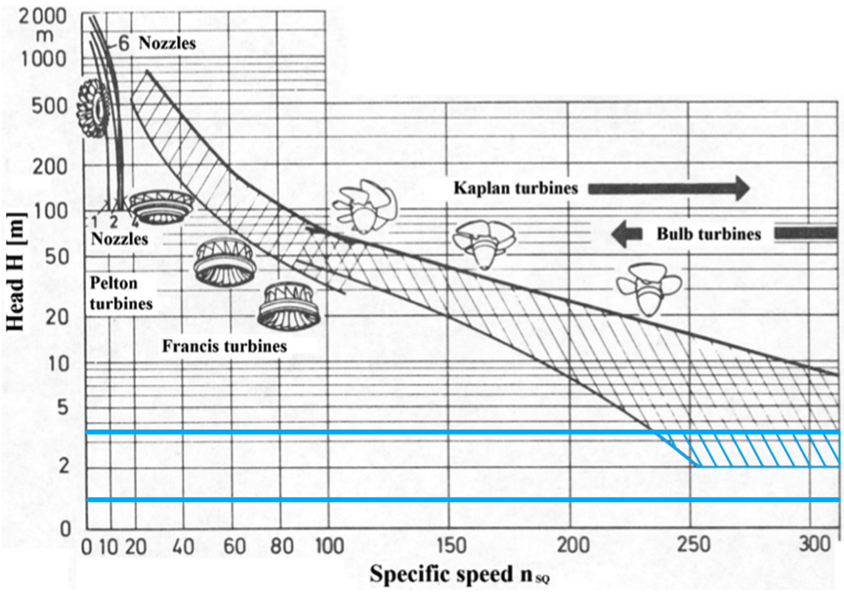


Figure 3.3: Operation range of the three main turbine types based on head H and specific speed n_{sq} (Krzemianowski & Steller, 2021)

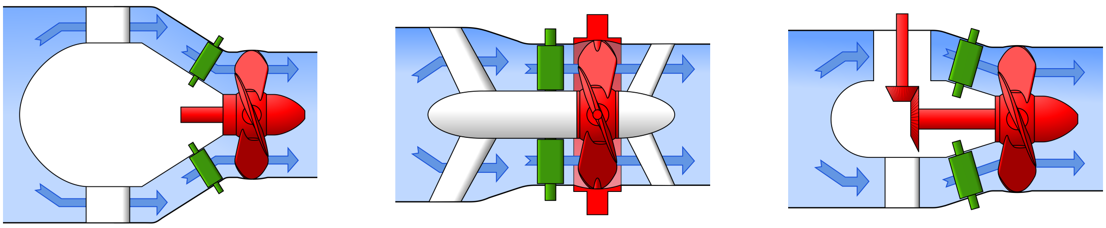
3.2.1. Axial turbines

An axial turbine is a reaction turbine using propellers comparable to those used for ship propulsion. The most common axial turbines are the bulb, straflo, tube, and Kaplan turbine. The Kaplan turbine will not be discussed as it does not resemble any existing marine application. The bulb turbine, figure 3.4a, has the most flow disturbance of the axial turbines, as the generator is installed within a sealed unit and placed in the incoming water flow. The horizontal axis propeller is commonly a variable pitch propeller. The straflo turbine, figure 3.4b, is similar to the bulb turbine except for the placement of the generator. The generator is placed at the rim of the blades. This ensures a better flow to the turbine blades. The tube or tubular turbine, figure 3.4c, transfers the rotation of the blades through a shaft to an external generator. Lastly, there is the Kaplan turbine. This turbine has the most adjustability due to the adjustable pitch of the blades and inflow gates. This allows the turbine to operate in a broad operational regime (U.S. Department of Energy, 2022).

The kinetic power generated by an axial turbine is the amount of power in the flow multiplied by the C_p of the turbine, shown in formula 3.9. The efficiencies of these turbines vary between $\eta =$ 0.8 - 0.95. This depends on more conditions than just the turbine design, such as head and flow disturbances (Gordon, 2001). The efficiency of a turbine on board a yacht will be lower as the turbine will not be fully encased in a tube but instead be in open water or only encased by a relatively short nozzle. The power coefficient for axial turbines can surpass the Betz limit as they are not in an open flow. However, when the machines are placed in open flow underneath a vessel, the Betz limit is the maximum achievable value for C_p. This formula could thus also be applied for yacht hydro generation.

$$P_{kin,max} = \frac{16}{27} \cdot \left(\frac{1}{2} \cdot \rho \cdot A_0 \cdot V^3 \right) \tag{3.9}$$

Axial turbines are the most likely to be placed on board yachts and are best compared with marine thrusters. The bulb turbine shares most similarities with a podded thruster with a built-in electric motor. The tube turbine resembles the configuration of a marine thruster with a z-drive (Wartsila, 2023). The straflo turbine is comparable with a rim-driven thruster, even though the concept varies slightly.



(a) Bulb turbine **(b)** Straflo turbine **(c)** Tube turbine

Figure 3.4: Various axial turbine types

Tidal turbines

Previously mentioned axial turbines are all mounted inside a duct or pipeline system. An example of an open flow turbine is the tidal turbine, figure 3.5, which operates in open flow similarly to wind turbines. These turbines will reach lower efficiencies and power coefficients of about C_p = 0.5, as they are mounted in a free flow and adhere to the Betz limit (Payne et al., 2017). The concept is similar to the bulb or the tube turbine where the generator is either in the pod or mechanically transferred through the tower to an external generator (Bahaj et al., 2007). Currently, from all turbines, the setup of the tidal turbines in open flow comes closest to the podded thrusters on yachts.

For these turbines, the tip vortex losses become more apparent, influencing the designed aspect ratio of the blades. The losses should be assessed to determine if adding a nozzle could improve efficiency. However, as the introduction of a nozzle considerably increases drag, tip vortex losses would have to be significant to be compensated with a nozzle.

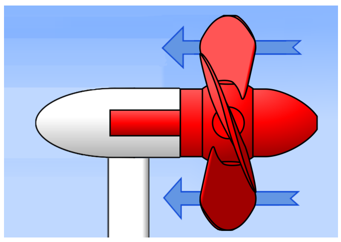


Figure 3.5: Tidal turbine

Ram air turbines

An example of a turbine designed to operate on a moving vehicle is a Ram Air Turbine (RAT). The RAT is an emergency turbine located on the wing or fuselage of an aircraft. It is deployed to provide hydraulic pressure or electrical power when aircraft lose electrical power or in case of an engine failure.

The turbine is similar to the tidal turbine in design and operates using the same principles. The main difference is the blade design. As it is deployed on fast-moving aircraft, the RAT is designed accordingly, with high aspect ratio blades for maximum efficiency. (Heritage Concorde, 2023)

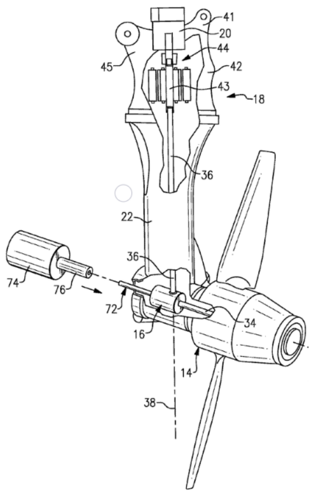


Figure 3.6: RAT (Russ & Larson, 2011)

3.2.2. Turbine overview

There are various means of hydro generation. Based on the physics, most of these solutions will not work on yachts due to the requirement for a large flow or a high-pressure head. Axial turbines seem to be the most promising solution as these work in low-pressure heads, which is the situation surrounding the yacht's hull. The Betz-limit shows that, as long as the turbine is in a free flow, the amount of energy that can be extracted from the flow will not surpass the $C_p = \frac{16}{27}$ level. The assembled literature on hydro generation turbines in this chapter has been summarized in table 3.1.

Overall, the information this section provides sets the basis for hydro generation and which options could be implemented on a sailing yacht. This makes it easier to filter the possible turbines on their practicality on board yachts. Using this, the efficiency of current solutions is established, and the physics is applied as the basis for the to-be-designed method.

Table 3.1: Summary of literature on hydro turbines

	Water wheel	Tidal	Bulb	Straflo	Tube	Kaplan	Francis	Pelton
Head	1	2	2	2	2	3	4	5
Max C_p, η	C_p = 0.3 - 0.4	C_p = 0.5	η = 0.8 - 0.95	η = 0.8 - 0.95	η = 0.8 - 0.95	η = 0.8 - 0.95	η = 0.8 - 0.95	η = 0.9
Similarity with marine solution	3 *	1	2	2 **	1 ***	5	5	5
Relative size	5	3	3	3	3	4	4	1
Requirement for ducting	1	1	1	5	1	5	5	5
Applicable in yachting	2	1	1	3	1	5	5	4

Additional info:
* Speedmeter
** Rim thruster
*** Sail drive / Z-thruster

Legend

	Head	Similarity	Size	Ducting	Applicable
1	Very low	Very high	Very small	No	Very likely
2	Low	High	Small	-	Likely
3	Medium	Medium	Medium	-	Medium
4	High	Low	Large	-	Unlikely
5	Very high	Very low	Very large	Yes	Very unlikely

3.3. Complications of a turbine on a yacht

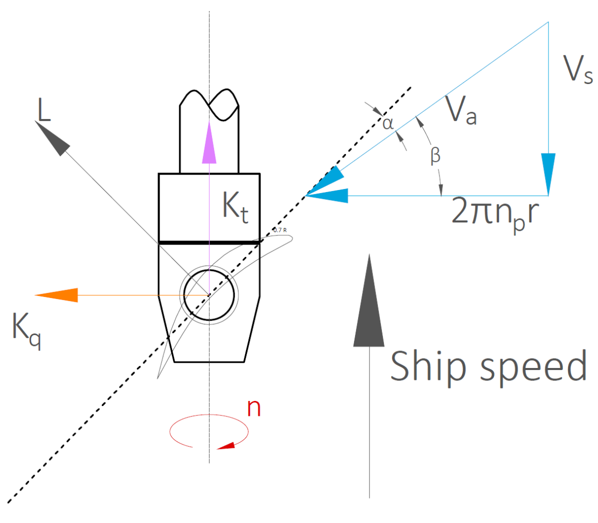


Figure 3.7: Standard definitions

Every modern sailing yacht has a propeller for mechanical propulsion, which can be used for hydro generation. However, a propeller adds momentum to a flow, and a turbine is designed to extract the maximum energy from the available flow momentum. These are fundamentally different objectives combined with different physics. Propellers will generate a contracting flow and turbines an expanding flow. And the flow around the blade is dissimilar for turbines and propellers. For propellers, lift is generated in the forward direction and delivers propulsion. For turbines, this lift is generated backward as drag. This is achieved by altering the angle of attack. The main problem is the required shape. The shape differs for an optimal propeller from that of an optimal turbine. There are two adjustments that (partially) overcome this problem, either by adjusting the flow direction or the pitch of the blades. This section will discuss these solutions.

To better understand these adjustments, two definitions are emphasized: the two types of propellers and the four operation quadrants. There are two types of propellers: fixed-pitch propellers (FPP) and controllable-pitch propellers. When using a FPP, the pitch of the blades cannot be adjusted. The propeller is designed to operate well in one operating point. Outside this point, the propeller will operate but in a non-optimal way. The whole field of operation of the propeller is described in the four quadrants diagram. This diagram used for the *Wageningen B series* by van Lammeren et al. (1969), is defined by advance ratio (J) and K$_t$, K$_q$. J is calculated as shown in formula 3.10. The standard definitions of the forces and directions are presented in figure 3.7. This includes the angle of attack α and hydrodynamic pitch angle β.

$$J = \frac{V_a}{n \cdot d} \qquad [\text{-}] \tag{3.10}$$

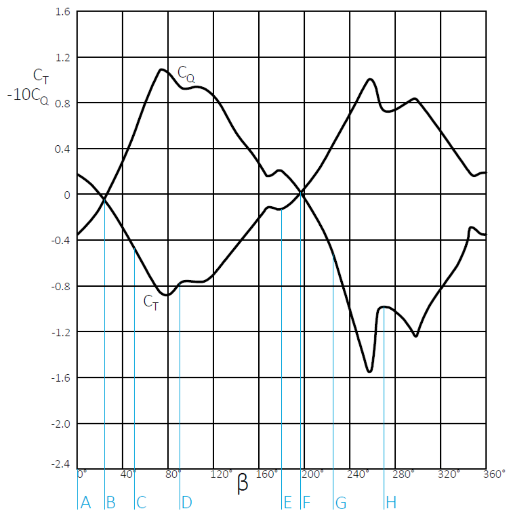
There are four quadrants for a propulsion propeller to operate in:

- In the 1st quadrant, $V_s \geq 0$, $n > 0$ and this is a normal forward operation;
- In the 2nd quadrant, $V_s \leq 0$, $n > 0$ and this is forward thrust at negative speed;
- In the 3rd quadrant, $V_s \leq 0$, $n < 0$ and this is a reversing propeller during stopping manoeuvre;
- In the 4th quadrant, $V_s \geq 0$, $n < 0$ and this is a normal astern operation.

Appendix B.1 provides an overview of a fixed-pitch propeller during propulsion in the four quadrants.

The second propeller type, a CPP, provides adjustability to the blade's pitch. A CPP also allows the user to choose the preferred level of hydro generation depending on the desired sailing speed. A common problem for sailing yachts with a FPP occurs during motor sailing, as this requires the propeller to operate in a condition it was not necessarily designed for. The design of a conventional propulsion system with an FPP is based on one operating condition. A CPP propulsion system can operate in multiple conditions and propulsion quadrants. This reduces the efficiency in a specific operating point compared to the FPP but increases the overall efficiency of the propeller. In the second and third quadrants, a CPP also provides better-optimized propulsion as the angle of attack can be reduced. This is presented in appendix B.2 as determined by Schouten (2016).

To explain hydro generation in the four quadrants, the definition by Kuiper (1991) is adopted. This method shows the coefficients K_t and K_q as a function of the hydrodynamic pitch angle β. Several points of interest occur by rotating the inflow β over a fixed blade profile. In figure 3.8, points of interest on a fixed blade are shown:



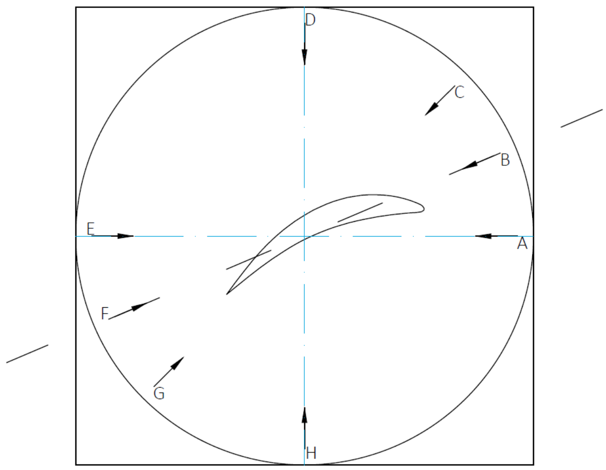


Figure 3.8: Four quadrants and the hydrodynamic pitch angles on a blade

- **A -** the starting point of normal propulsion;
- **B -** the point of zero angle of attack on the blade profile (leading edge side), normal propulsion ends here, and generation in the first quadrant starts;
- **C -** the end of generation in the first quadrant;
- **D -** the point where the flow comes from if the vessel is moving forward and the propeller is stationary;
- **E -** the starting point of reverse propulsion;
- **F -** the point of zero angle of attack on the blade profile (trailing edge side), reverse propulsion ends here, and generation in the third quadrant starts;
- **G -** the end of generation in the third quadrant;
- **H -** the angle where the flow comes from if the vessel is moving astern and the propeller is stationary.

This shows that a fixed pitch propeller can generate in two quadrants: the first and third. First quadrant generation occurs during ordinary sailing when hydro generation is switched on. The third quadrant is only achieved if one of two changes occur: either by sailing astern, which is very unlikely for a sailing yacht, or by turning the propeller around. This is done using a propeller mounted to a thruster as long as the thruster can turn at least 180 degrees. The inflow direction will change, achieving generation in the third quadrant. Appendix B.3 shows the four quadrants defined by Kuiper (1991) for a fixed pitch propeller. Second and fourth-quadrant generation is impossible due to the significant angle of attack created in these situations. For an FPP, a compromise can be found for the propeller to work well for propulsion and generation, with balanced efficiency in both modes for low-speed ships (Liu et al., 2018). However, changing the propeller's pitch with a CPP increases the efficiency by adapting it to a changing flow.

A CPP can generate more efficiently than an FPP as the pitch is changeable to the desired amount of extracted torque. Thereby optimizing the amount of generated energy, as more extracted energy leads to more resistance. This process is regulated using a CPP. This results in more or less resistance, causing a change in ship speed. A CPP also allows for more freedom in choosing the desired output and accompanying loss of ship speed. Appendix B.4 shows generation using a CPP in the four quadrants. The second quadrant is left out as the pitch distribution over the propeller blade is in the wrong direction. This results in significant angles of attack on the stem and tip and thus limits efficiency. Generation in the third and fourth quadrants will also require the propeller to be mounted to a pod that can turn at least 180 degrees. Adding a CPP on a pod is, during the writing of this report, uncommon but possible and is therefore considered state-of-the-art.

The standard range of a CPP is around 100 to 110 degrees. Propeller blades are set to feathering mode at 90 degrees, which provides the least resistance during sailing, and rotated till about -20 degrees for better performance when motoring astern. A vessel equipped with a CPP will usually operate without a clutch, so the propeller always turns in one direction. The amount of thrust delivered and the direction of thrust are controlled using the propeller's pitch. An alternative for reaching hydro generation in the third quadrant is applying a new kind of CPP. One that can achieve pitch angles over a 210-degree range (Shipmotion, 2023).

The decision to generate in a specific quadrant is based on efficiency and power production. Research at *MARIN* by Schouten (2016) claims that power generation in the third quadrant provides a 30% efficiency increase relative to the first quadrant. This is caused by a proper camber in the flow direction and outweighs the negatives of switching the original trailing edge for the leading edge. Ultimately, the final angle at which the CPP blade is oriented during hydro generation is chosen by whether maximum speed or maximum energy production is the goal.

3.4. Options for hydro generation

There are many optional hydro generation system parts, making many combinations possible. The dominant partition for the options is the difference between an integrated solution in the propulsion system or a separate dedicated hydro generation device. From an efficiency perspective, separating the propulsion and generation systems is beneficial. This allows both systems to be optimized for their specific purposes. Section 3.3 showed that reaching maximum efficiency for both generation and propulsion on one propeller is impossible. By splitting the tasks over two propellers, two higher efficiencies are achieved. Additionally, the speed through the propeller is the most dominant variable in the power output equation 3.9. The influence is to the third power compared to the propeller disk area and power coefficient. If the generating propeller is placed in water with a 5% higher speed, the output in watts is $(1.05)^3 = 1.16$, 16% higher. The water speed around a yacht's hull can vary and depends on the hull's shape. CFD calculations like the one in figure 3.9 show these changes in water speed. In this particular design, the water speed is the highest midships. This would be the optimal location for hydro generation. However, any appendages placed here will also experience the most drag.

An integrated system is more space efficient as parts of the system are also used for propulsion. This does come at the cost of lower outputs due to the lack of dedicated, and thus optimized, parts. In an integrated hydro generation system, the separate components are constricted by the selected options for the propulsion system. This system is deemed more important in most designs and thus leads the decision-making process. Combined with the choice for a FPP or CPP, an overview is presented in figure 3.10. The number of turbines could also be varied, this is not taken into account in the overview.

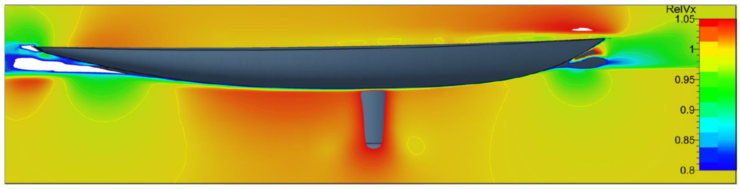


Figure 3.9: CFD calculation by DNA of water speed around a sailing yacht hull

As hydro generation is an upcoming technology, several developments regarding the topic were found. Most of these developments are not focused on hydro generation but can be applied to it. As a hydro generation system is linked to the propulsion system, advancements in this field are also interesting for hydro generation. Two new products were deemed state-of-the-art: a controllable pitch propeller with extended pitch range and a controllable pitch propeller on a thruster.

CPPs on sailing yachts are usually designed to operate with a range of 100 to 110 degrees, from feathering to just past zero pitch. A new state-of-the-art Hybrid Controllable Pitch Propeller (HCPP), which can surpass this and turn 210 degrees, has recently been launched. According to the interviewed Bruggeman (Personal communication, 2023), the prototype was delivered in 2019. The first commercial units are currently in operation. The HCPP has an electro-magnetically controlled Pitch Control Unit (PCU). The PCU is connected to the turning mechanism in the hub via a tension rod. The PCU transfers the thrust using pressure bearings that lock the system. The system contains parts designed to encounter semi-elastic transformations that complicate the process.

Another development is the introduction of CPP on a thruster. The technology is not new, with larger units available for double-ended ferries. Since 2020, this product has been delivered by companies such as Brunvoll (2023) and Schottel (2023). Around the same time, the system was introduced on yachts by Baltic with their *Retractable Propulsion System (RPS)* (Baltic Yachts, 2023). The system is produced by Hundested (2023) and is available as the retractable propulsion system (RPS) and the fixed saildrive propulsion system (SPS). The latter will be installed on board DNA's project *Zero*. On their website, Hundested (2023) claim 30% more efficiency during hydro generation as both pods rotate 180 degrees, allowing 3^{rd} quadrant regeneration.

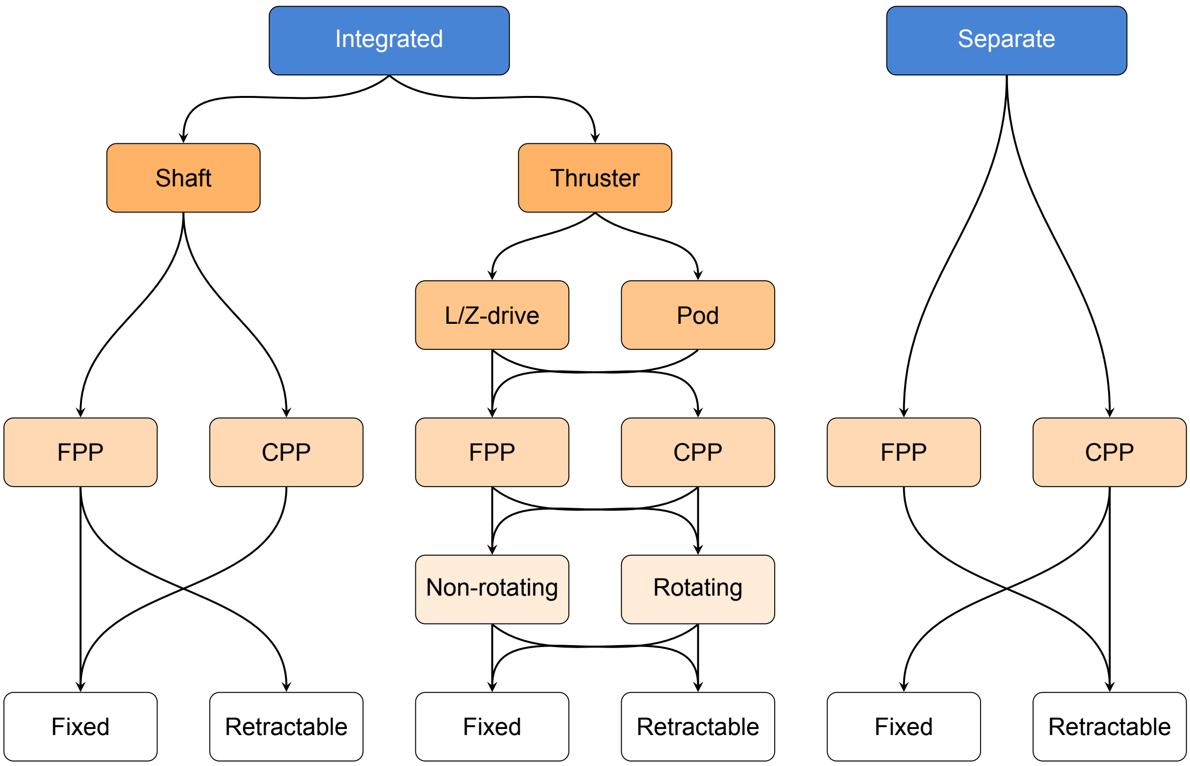


Figure 3.10: Available combinations of hydro generation options

3.5. Overview

This chapter answers the question: *What solutions for hydro generation are currently applied on sailing yachts, and what solutions can be applied in the future?* With all recent developments, it is hard to pinpoint what has not been done yet. The existing hydro generation solutions are mainly installed onto the propulsion system. There are options on the market for separate systems, but these are mostly standard consumer systems implemented on smaller pleasure craft. Large custom solutions are divided into multiple categories. Possible combinations of hydro generation are presented in figure 3.10.

Apart from a couple of missing lines, most combinations are possible. The critical points to consider are location, generation quadrant, and the number and size of propellers. The data found during the research for this chapter have been implemented into the design method to provide insight into the output of various hydro generation configurations.

The idea of hydro generation is gaining traction, and so are the developments in the hydro generation field. With the added efficiency in the third quadrant, most advancements are found in products that allow this type of generation. The energy conversion and storage efficiencies are already relatively high, so the developments in this area are less significant. Still, energy storage systems are expected to keep developing in the coming years with new battery technologies or alternatives such as fuel cells.

4
Scenario and method introduction

Sub-question three and four remain to be answered: *How can a selection method be formed to determine which hydro generation configuration would suit a specific sailing yacht (or refit) best?* and *To what extent does the implementation of hydro generation influence sailing yacht design, and which choices indicate the limit of implementation?* A novel design method is created for this thesis to answer these sub-questions. It is tested using a scenario created to represent a realistic use case for a sailing yacht. Sub-question three relates to the creation of this design method, and sub-question four to the produced results. The specific usage scenario is introduced first as background for the method's calculations.

4.1. Scenario

The scenario has been set up to determine the performance of a hydro generation system on board a yacht. It presents a realistic situation and requirements for a sailing yacht. A scenario was selected that could genuinely be influenced by hydro generation: an ocean passage. An ocean passage is a scenario that provides an opportunity for many sailing hours within its duration, combined with a constant hotel load. The goal is to perform a fuel-minimizing ocean passage. This means that the hotel load is compensated by utilizing hydro generation during the crossing.

Four rules have been set to reduce the variation between scenario runs. Firstly, if the engine needs to be turned on because the wind becomes unfavorable, the hotel load is covered by the engine. However, the battery is not charged in this situation. Secondly, the propulsion engine is used if the yacht cannot reach 80% transit speed using wind and sails. If 120% transit speed is reached by only using wind and sails, hydro generation will be initiated. Thirdly, no other energy generation, such as solar or wind power, occurs. Lastly, a diesel generator supplies the hotel load if the battery charge reaches zero. However, this generator will not charge the batteries.

A common ocean crossing for many super yachts is from the Mediterranean to the Caribbean when the European summer has ended. In this scenario, the sailing yacht leaves Gibraltar on a full battery and sets sail for the West Indies. Realistically, a crossing would be planned based on the weather and the best route available considering the wind. To increase the comparability of the results, the decision was made to leave for the trip regardless of the weather. The great circle route is sailed, even if a longer distance passage would be faster. Predicting the wind that a vessel might encounter is dependent on a large amount of variables. For the scenario, a simplification is made by using a statistical approach. This is run multiple times using a prediction for the chance of free sailing and hydro generation. A trip is considered a success if the crossing is completed without additional use of the generator to supply the hotel load. A success rate is determined by dividing the number of successful trips by the absolute number of crossings. The following scenario data is used during calculations:

- **Duration:** 1 trip (Approx. 300 hrs)
- **Route:** Gibraltar - West Indies
- **Length:** 3200 nm
- **Wind data:** Gibraltar - West Indies (October - November, 1979 - 2009)

The wind data is collected using a weather mapping calculation by DNA. A vessel completes the trip 190 times in a straight line, as shown in 4.1, at 12 knots of constant speed. The crossing is made in October or November, the usual time for a trip like this. A trip is completed every ten days using historical wind data from 1979 to 2009. All data is summarized in a wind probability matrix with wind speeds and directions. This matrix is used as an input for the method.

Figure 4.1: Route from Gibraltar to West Indies

Two yachts have been selected for the scenario: one is an existing 31-meter yacht, and the other is a concept 51-meter yacht currently being built. This decision was made to test the method's accuracy using an existing sailing yacht, while the method's usefulness for future projects was tested using a concept yacht. The lengths were selected to cover the method's entire usable range.

The selected 31-meter yacht *Perseverance*, equipped with a shaft for first quadrant generation, is a DNA design also used to test the method during the coding process. The 51-meter hypothetical yacht is based on the design for *Project Zero*. This yacht is outfitted with turning thrusters, allowing it to generate in the third quadrant. An overview of all the input data used in the method for both yachts is presented in appendix E. Both sailing yachts are outfitted with a CPP and can adjust the blade pitch to optimize generation. For this scenario, the CPP can be set to four settings: feathering, maximizing η, middle, and maximizing C_p. The middle setting is determined by finding the halfway point between max η and max c_p on the propeller curve.

4.2. Method overview

The yachts are examined in four main areas of interest using the scenario:

1. a prognosis for the hydro generation systems output based on the given parameters;
2. the physical impact on the system;
3. the impact on fuel consumption and emissions;
4. and the impact of sailing regions and yacht usage.

A method was constructed to complete this examination using several series of calculations. For the physical impact on the system, a variation in propeller diameter is analyzed, and the size of the generator and batteries are estimated. And the predicted energy balance of the yacht provides insight into the fuel consumption. Applying wind data from other routes and alternative operational profiles shows a projection of their impact on the system.

The design method is divided into four parts: the basis, a propeller variation, a generator size prediction, and an energy balance determination. The first block serves as the input for the method and provides all required calculations for the hydrodynamics of hydro generation. The other parts do not necessarily correspond with the areas of interest. Instead, they are divided into a coherent order of calculation. The method is coded in the programming language *Python*. Figure 4.2 provides an overview of the design method. Blue blocks serve as input or output. All the calculations are performed in the orange blocks.

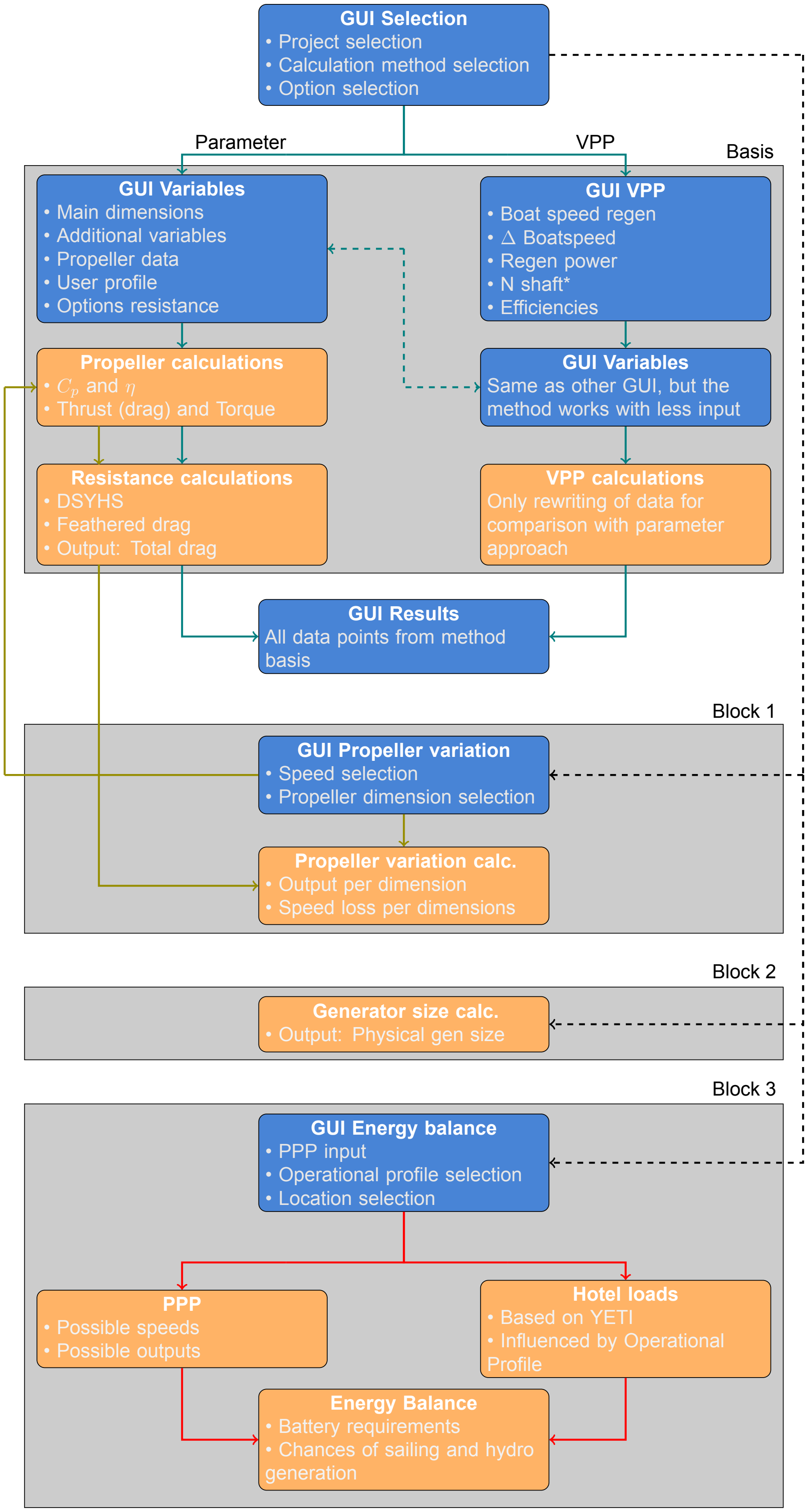


Figure 4.2: Overview of method

5
Basis: Hydro generation output

The first area of interest for assessing the scenario is determining the performance of a hydro generation system and its possibilities. This is achieved by calculating the produced energy output of the system. These preliminary calculations are completed in the first part of the method: the basis.

Two paths are available to complete the preliminary calculations: with early-stage design variables or VPP data. The method is intended to be used with the variables known during the early design stages when a VPP cannot be run yet. The second approach is used in a later stadium to check the outcome of the preliminary estimations. The process begins with the input window, where all the necessary variables for completing the calculations are entered. When the project has already been run before, the last input values will be loaded into the Graphic User Interface (GUI). For the VPP option, an additional window will open in which the data from a VPP run can be copied. Examples of the GUI's used are presented in appendix E

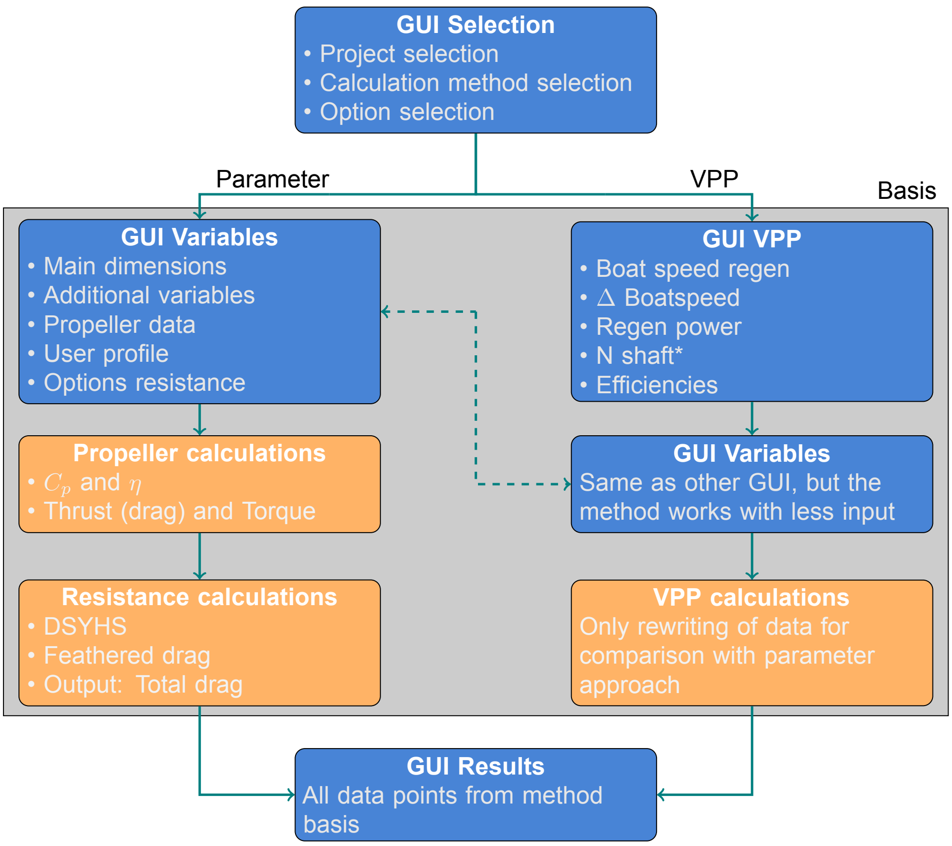


Figure 5.1: Overview of basis

Parameter based

If the 'Parameter' option is selected, the input window will be for the variables required for calculating the propeller characteristics, resistance, and output. This is separated into four groups: main dimensions, additional variables, propeller data, and optional inputs.

The main dimensions and optional inputs are for the resistance calculations. This includes the dimensions of the canoe body and appendages. As the appendages are not required for the resistance calculations, they are included in the optional inputs. The propeller data is used to calculate the propeller characteristics.

Two calculations are performed for this approach: the propeller and resistance calculations. The first one provides the drag for different propeller settings. The second one determines the resistance of the yacht, using the 1998 Delft Systematic Yacht Hull Series (DSYHS) (Keuning & Sonnenberg, 1998).

VPP based

If the 'VPP-based' option is selected, the input window changes to an input for the results from a velocity prediction program (VPP). This is separated into three groups: boat speed, delta boat speed, and regenerated power, in which data is directly copied from the output Excel of the VPP.

The output in the Excel consists of a 23 x 5 grid with data, so 23 inflow angles for the wind and five wind speeds. These points are sorted based on boat speed and put into a single-row array to generate the same results as the other calculation method. The other grids are sorted using indexing, making the data in each of the four arrays uniform.

The VPP used for this is one designed in-house at DNA. The VPP performs an iterative calculation to find a balance in four out of six degrees of freedom. The main objective of the VPP is to determine the speed potential and not necessarily the possible output for hydro generation. Generated data per VPP run has limited use for the method.

The VPP approach within the method does not necessarily provide new data but transforms the generated data from the VPP into similarly shaped outputs as the parameter approach. This means that the effect of the wind is removed, and the data is plotted for steps in boat speed. This way, a fair comparison is created. Some of the input from the parameter approach needs to be reused for this data conversion. A downsized input window similar to the parameter one is used for this.

Differences between options

The main difference between the two options is the intended use. While both provide similar results, the means of getting there vary. The parameter version is a first estimate and provides one iteration to determine the outcome. It operates using a limited set of variables compared to the VPP version. This uses data from the actual VPP and all of its required input. This allows the VPP itself to iterate until a balance is reached. The generated data is more accurate as the calculations are based on fewer estimates and more data.

The parameter approach serves the method's main goal and provides an answer as precise as attainable during the early design stage. The VPP approach serves as a check that can later be performed. To check all results, six VPP runs are required. The VPP only works for one pitch setting, and the parameter approach asses six pitch settings simultaneously. This makes the VPP method more computationally intensive.

5.1. Basis calculations

The calculations performed in the method's basis are for the resistance, based on the DSYHS Keuning and Sonnenberg (1998), and for the propeller characteristics. The propeller calculation provides the yield of hydro generation. Three operating points are considered: maximum efficiency, maximum generated power, and a middle point. The resistance calculations provide insight into the losses and show how much speed is lost during generation.

5.1.1. Propeller characteristics

The regeneration propeller curves are constructed using K_t and K_q data from a propeller for different hydrodynamic pitch (β) angles and $\frac{P}{D}$ values. For this thesis, the data for the B4-70 propeller in undisturbed flow is used as published by MARIN van Lammeren et al. (1969). Propeller curves are constructed for both the first and third quadrants. The added drag from hydro generating is determined for the sailing speed by selecting an operating point on one of these curves. These curves are set up, per $\frac{P}{D}$ value, using calculations derived from Klein Woud and Stapersma (2002):

1. First, the inflow angle is determined by finding the beta at which K_q equals zero. This is the first beta of each $\frac{P}{D}$ curve. A list of increasing betas is established for the calculation steps.
2. The angle of attack is calculated by subtracting the original $\frac{P}{D}$ from each beta.

$$\alpha = \beta - \text{tan}\left(\frac{P}{D} \cdot \frac{180}{0.7 \cdot \pi}\right) \qquad \text{[deg]} \qquad (5.1)$$

   This value serves as a check and is not used in further calculations.
3. The rotation speed of the propeller is calculated using the flow speed and each beta. The pitch is retrieved at 70% of the blade radius, where the average pitch of the blade is retrieved, as per ITTC (2008) regulations.

$$n = \frac{V_w}{0.7 \cdot \pi \cdot d \cdot \text{tan}(\beta)} \cdot 60 \qquad \text{[rpm]} \qquad (5.2)$$

4. The speed of the propeller blade through water using the velocity of the propeller through water and the turning speed of the propeller.

$$V_{\text{blade}} = \sqrt{(V_w)^2 + (0.7 \cdot \pi \cdot d \cdot n)^2} \qquad \text{[m/s]} \qquad (5.3)$$

5. With the lists of betas, new lists of K_t and K_q are compiled using Cubic spline interpolation.

$$S(x) = \begin{cases} K_{t,1}(x), & \beta_0 \leq \beta \leq \beta_1 \\ \quad ... \\ K_{t,i}(x), & \beta_{i-1} < \beta \leq \beta_i \\ \quad ... \\ K_{t,n}(x), & \beta_{n-1} < \beta \leq \beta_n \end{cases} \qquad (5.4)$$

   Where each

$$K_{t,i} = a_0 + a_1 \cdot \beta + a_2 \cdot \beta^2 + a_3 \cdot \beta^3 \qquad \text{[-]} \qquad (5.5)$$

   for $(a_3 \neq 0)$ is a cubic function, $i = 1, .., n$. Coefficients $a_{0,1,2,3}$ of the cubic spline polynomial are determined during the spline construction using the arrays for K_t and β.
6. The thrust and torque are calculated using previously determined values for K_t, K_q, v_{blade}, and the area of the propeller.

$$T = \rho \cdot \frac{1}{2} \cdot V_{\text{blade}}^2 \cdot \frac{\pi}{4} \cdot d^2 \cdot K_t \qquad \text{[kN]} \qquad (5.6)$$

$$Q = \rho \cdot \frac{1}{2} \cdot V_{\text{blade}}^2 \cdot \frac{\pi}{4} \cdot d^3 \cdot K_q \qquad \text{[kNm]} \qquad (5.7)$$

7. The power on the propeller and the power of generation calculated using the thrust and torque lead to the results for the $\frac{P}{D}$ plots: C_p and η

$$P_{prop} = Q \cdot 2 \cdot \pi \cdot n \qquad \text{[kW]} \qquad (5.8)$$

$$C_p = \frac{P_{prop}}{\frac{1}{2} \cdot \rho \cdot V_w^3 \cdot \frac{\pi}{4} \cdot d^2 \cdot \#} \qquad [\%] \qquad (5.9)$$

$$P_{regen} = T \cdot V_w \qquad \text{[kW]} \qquad (5.10)$$

$$\eta = \frac{P_{prop}}{P_{regen}} \qquad [\%] \qquad (5.11)$$

The resulting plot of the data points created using C_p and η for the first quadrant is given in figure 5.2. The optimal point in the figure is the upper right corner with both a high C_p and a high η. This means a high energy output for low losses. All calculated curves for the six different $\frac{P}{D}$ ratios have been plotted in the left part of the figure. Only the data points have been plotted in the right plot, combined with a curve representing the maximum efficiency values. Although all data points in the figure represent viable options, only the points closest to the upper right corner will be used as these form the combination of the best options. All points between the maximum C_p and maximum η form a curve with viable options. There is a better option for all other points in the graph that are not on this line with either a higher efficiency or a higher energy output. A middle point at the $\frac{50}{50}$ position for efficiency is added to provide future calculation points for the system's output.

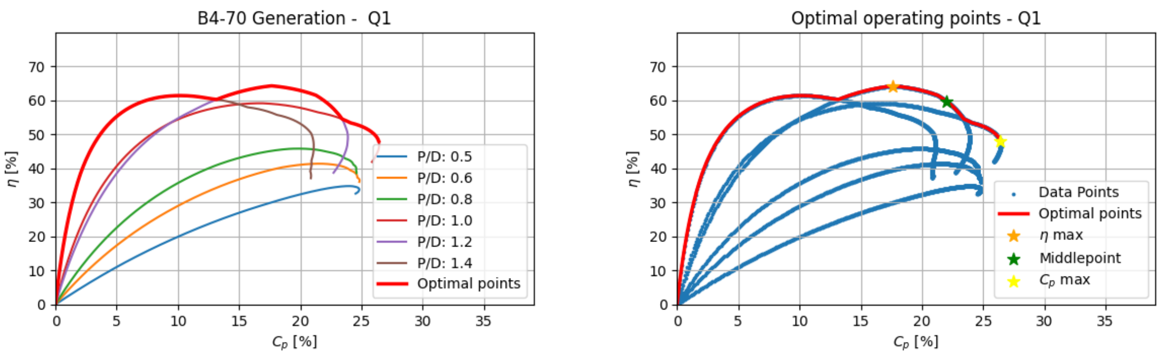


Figure 5.2: $\frac{P}{D}$ curves for Q1 for B4-70 propeller as derived from K_t and K_q

The process is repeated for generation in the third quadrant, as presented in figure 5.3. The maximum line for hydro generation in the third quadrant is for higher efficiencies and power coefficients, resulting in a curve located further right and up than the first quadrant. This is caused by propulsion propellers being better suited for generation in the third quadrant than the first, as explained in section 3.3. The combined six points derived from the two combinator curves for hydro generation will be used in further calculations.

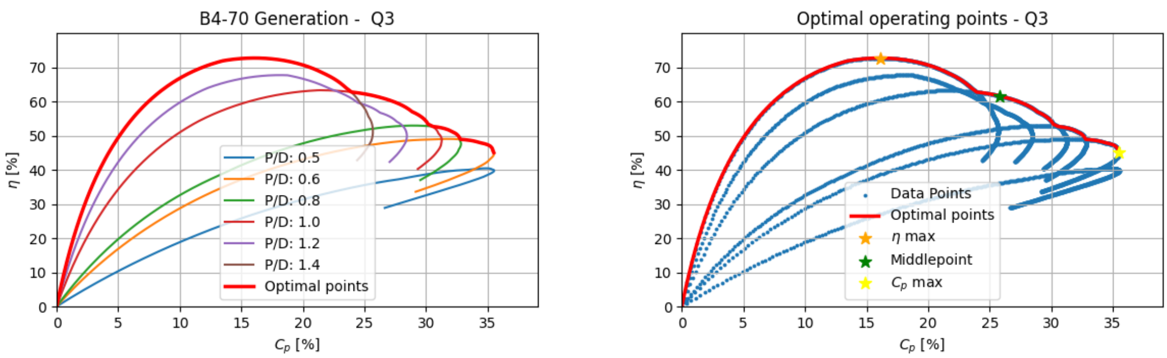


Figure 5.3: $\frac{P}{D}$ curves for Q3 for B4-70 propeller as derived from K_t and K_q

5.1.2. Delft systematic yacht hull series

The DSYHS by Keuning and Sonnenberg (1998) is a vast data set of resistance data from which a series of polynomial functions are derived. These functions serve as the basis for the resistance calculations in the designed method. The upright hull resistance is separated into five categories:

1. The frictional hull resistance R_{fh} in [N]

$$R_{fh} = 0.5 \cdot \rho \cdot V_{ship}^2 \cdot WSA_c \cdot \left(\frac{0.075}{\left(log\left(\frac{V_{ship} \cdot 0.7 \cdot l_{wl}}{v_{water}} \right) - 2 \right)^2} \right) \tag{5.12}$$

2. The residuary hull resistance R_{rh} in [N]

$$\frac{R_{rh}}{\rho \cdot g \cdot \nabla_c} = a_0 + \left(a_1 \frac{LCB_{fpp}}{l_{wl}} + a_2 \cdot Cp + a_3 \frac{\nabla_c^{\frac{2}{3}}}{A_w} + a_4 \frac{b_{wl}}{l_{wl}} \right) \frac{\nabla^{\frac{1}{3}}}{l_{wl}} + \left(a_5 \frac{\nabla_c^{\frac{2}{3}}}{Sc} + a_6 \frac{LCB_{fpp}}{LCF_{fpp}} + a_7 \left(\frac{LCB_{fpp}}{l_{wl}} \right)^2 + a_8 \cdot Cp^2 \right) \frac{\nabla^{\frac{1}{3}}}{l_{wl}} \quad (5.13)$$

3. The viscous rudder resistance R_{vr} in [N]

$$R_{vr} = 0.5 \cdot \rho \cdot V_w^2 \cdot WSA_r \cdot \left(\frac{0.075}{\left(log \left(\frac{c_{tip,r} + c_{root,r}}{2} \cdot \frac{V_w}{v_{water}} \right) - 2 \right)^2} \right) \cdot \left(1 + \left(2 \cdot \frac{t}{c} + 60 \cdot \left(\frac{t}{c} \right)^4 \right) \right) \quad (5.14)$$

4. The residuary keel resistance R_{rk} in [N]

$$\frac{R_{rk}}{\rho \cdot g \cdot \nabla_k} = a_0 + a_1 \frac{t}{b_{wl}} + a_2 \frac{t_c + z_{cbk}}{\nabla_k^{\frac{1}{3}}} + a_4 \frac{\nabla_c}{\nabla_k} \quad (5.15)$$

5. And the viscous keel resistance R_{vk} in [N]

$$R_{vk} = 0.5 \cdot \rho \cdot V_w^2 \cdot WSA_k \cdot \left(\frac{0.075}{\left(log \left(\frac{c_{tip,k} + c_{root,k}}{2} \cdot \frac{V_w}{v_{water}} \right) - 2 \right)^2} \right) \cdot \left(1 + \left(2 \cdot \frac{t}{c} + 60 \cdot \left(\frac{t}{c} \right)^4 \right) \right) \quad (5.16)$$

The frictional resistances are based on sailing speed and surface area, while the residuary resistance is calculated using coefficients from the DSYHS. The method also works when the keel and rudder have not yet been designed. By leaving these parts out, results do become less accurate. The total hull resistance is calculated by taking the sum of the five separate categories.

$$R_{hull} = R_{fh} + R_{rh} + R_{vr} + R_{rk} + R_{vk} \quad (5.17)$$

The resistance calculation using the DSYHS does not use the same step size as the method, so interpolation is used to fit a new line for the hull resistance. Figure 5.4 shows this line for *Perseverance*. It is stopped at a Froude number of 0.45 as results become less precise. Additionally, the yachts for which the method is designed are not expected to cross this number.

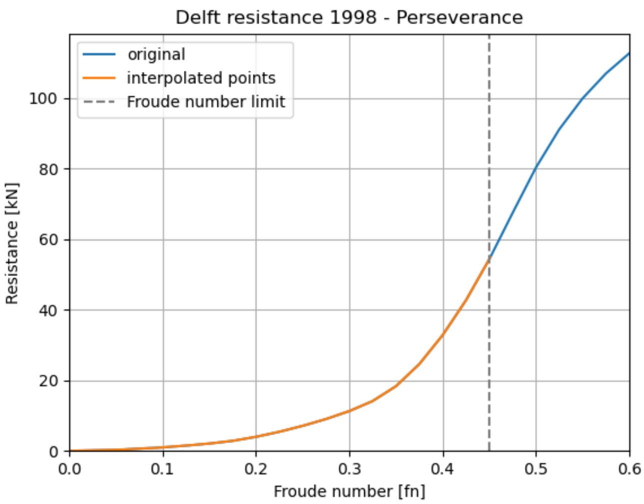


Figure 5.4: Interpolated line for *Perseverance* over DSYHS

5.1.3. Feathered drag

The feathered drag is the resistance the propeller and surrounding structures induce. The presumption for this calculation is that the propeller blades are pitched into a setting where the least resistance occurs. This resistance is added to the hull and appendage resistances to compile the total resistance in a free sailing condition. The feathered drag is determined by multiplying a Prismatic Parameter (PiPa) with the flow of water through the propeller:

$$R_{feathered} = PiPa \cdot p_{flow} = \left(\left(\frac{A_e}{A_0} \cdot A_0 \right) \cdot C_d \cdot \frac{A_p}{A_d} \right) \cdot \left(\frac{1}{2} \cdot \rho \cdot V_a^2 \right) \quad [N] \quad (5.18)$$

This formula is a combination made by DNA, simplifying several calculation methods. It encompasses all submerged propulsion system parts, such as hull bossing, shaft, struts, shaft brackets, and propeller. The formula is based on the propeller area. It uses a coefficient C_d for the drag and a factor of $\frac{A_p}{A_d}$ to account for the difference between the developed area and the projected area of the propeller.

Coefficient C_d for a feathered propeller is taken as 0.3 in the rest of this report based on the findings of MacKenzie and Forrester (2008). They conclude that this number is the correct coefficient for: 'fixed blades, shaft free to rotate, zero braking torque.' The same as the feathered condition. The factor $\frac{A_p}{A_d}$ is based on formula 5.19 by Gerr (1989), in the remainder of this thesis, this factor is considered as 0.85 based on an average $\frac{P}{D}$ of 1.

$$\frac{A_p}{A_d} = 1.0125 - \left(0.1 \cdot \frac{P}{D}\right) - \left(0.0625 \cdot \frac{P}{D}\right)^2 \qquad [-] \tag{5.19}$$

When calculating the resistance during generation, the feathered drag cannot simply be added as with free sailing. The resistance of the blades has already been taken into account with the calculation for the resistance due to generation. Now, only resistance induced by the supporting structure remains. This structure resistance includes all submerged propulsion system parts, including hull bossing, shaft, struts, shaft brackets, and propeller (except the blades). In-house data analysis at DNA concludes that half of the feathered resistance is generally equal to the resistance of the remaining structure 5.20. This formula is an approximation with no background in literature to support it. Still, the equation is used in further calculations in this thesis due to a lack of literature on the topic, and to preserve continuity with the other computations at DNA, further research is recommended for future works.

$$R_{structure} = \frac{1}{2} R_{feathered} \tag{5.20}$$

5.1.4. Total drag

Combining the hull resistance with the resistance for generation and subtracting half of the feathered drag provides the total resistance during generation in formula 5.21.

$$R_{total,gen.} = R_{hull} + R_{generation} + R_{structure} \tag{5.21}$$

The resistance at different speeds for point middle Q1 point is added in figure 5.5. It shows that the drag of the propeller increases with an increase in speed. The difference between the total and hull resistance increases as well. The middle point was selected as it is considered the balanced option and likely to be chosen during use. An overview of all six propeller settings for the same example as in figure 5.5 is provided in appendix C. The plot is stopped at Fr = 0.45 for the same reasons as explained in section 5.1.2.

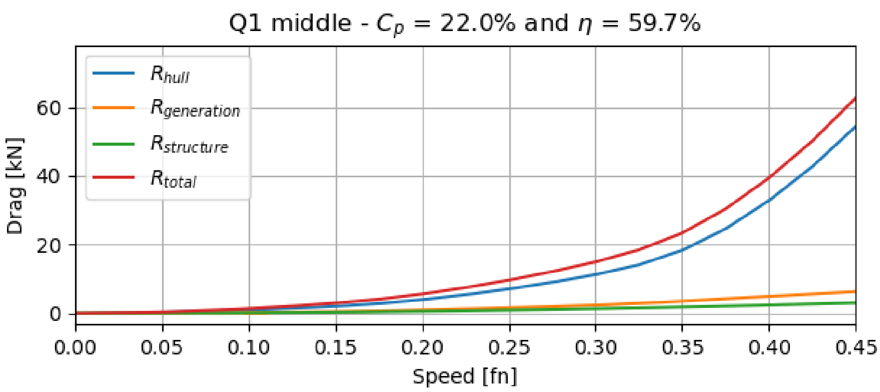


Figure 5.5: The resistance for the middle point in Q1 on board *Perseverance*

5.2. First results

The combined information of the resistance and produced power gives the first results of the method. This section will analyze these first results for both the parameter and VPP part of the method. The vessel used for the results in this section is the sailing yacht *Perseverance*, as applied in the scenario. The selected propeller is the B4-70 with the original 0.9-meter diameter. The results will be verified in the next section.

5.2.1. Power output parameters

The main results for the basis of the method are the outputs for the six propeller settings per vessel. The power output is measured at the connection point of the propeller and the shaft, so no losses have been accounted for yet. An example of the power output for the parameters option is provided in appendix D.

The middle Q1 point is also added in figure 5.6. Again, this point was chosen to represent the balanced point. It shows two plots overlaid with a combined x-axis representing the yacht's speed. The blue line is the maximum power output achievable per sailing speed for the parameters. The yellow line is the speed that would have been sailed during free sailing with the propeller in feathering mode. So, the horizontal distance between these lines is the speed the vessel loses when hydro generation is turned on. This is visualized at 12 knots free-sailing by: Δ *speed loss in kts*. This same speed loss is also presented as a percentage of the total sailing speed in the second plot with the y-axis on the right. The second added line shows the Δ *speed loss as %* for 12 knots free-sailing. The speed loss line shows that the relative losses decrease when speed increases. The resistance curve is the reason for the step-wise shape.

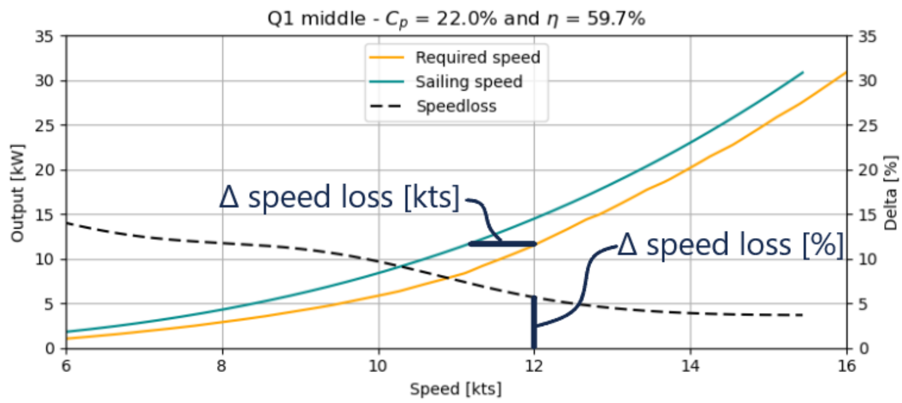


Figure 5.6: The results for the middle point in Q1 on board *Perseverance*

5.2.2. Power output VPP

The VPP performs nearly all the previous calculations but only for one predetermined propeller setting. The input from the VPP is rewritten so the results can be displayed similarly to the parameter approach. The data points were fitted using a fourth-order *polyfit* function as there is more variation between the points. This polyfit function applies the least squares method to find the best-fitting curve. The result for the middle Q1 point is provided in figure 5.7. This figure displays the speeds at which the yacht will sail and supports the decision to remove the first couple of knots from the plot and limit it to a Froude number of 0.45 as no higher speeds are expected.

5.3. Calculation check

The first results is reviewed by examining the differences and similarities between the VPP and the parameter method. The VPP does not provide all the intermediate answers. Still, the results for the resistance and power output are verified.

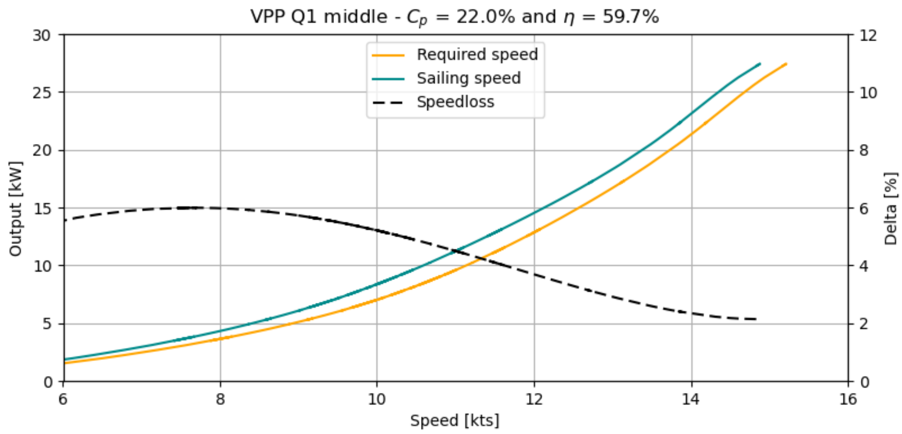


Figure 5.7: The results for the middle point in Q1 on board *Perseverance* as determined by the VPP

5.3.1. Resistance check

The resistance used in the calculations for both approaches is quite similar but not exact, as is seen in figure 5.8. The differences are caused by a simplified calculation with fewer parameters when the VPP is not used. The VPP also considers the difference caused by drift and resistance when heeling. This difference is noticeable at higher speeds, as seen in the figure at speeds above thirteen knots. When the design is more complete, CFD calculations might be performed. This can further change the resistance used in the VPP and make it more precise.

An important detail is the number of data points applied to determine the resistance curve. Fewer points will decrease the confidence in the results. In the provided figure, the decrease is noticeable under six knots.

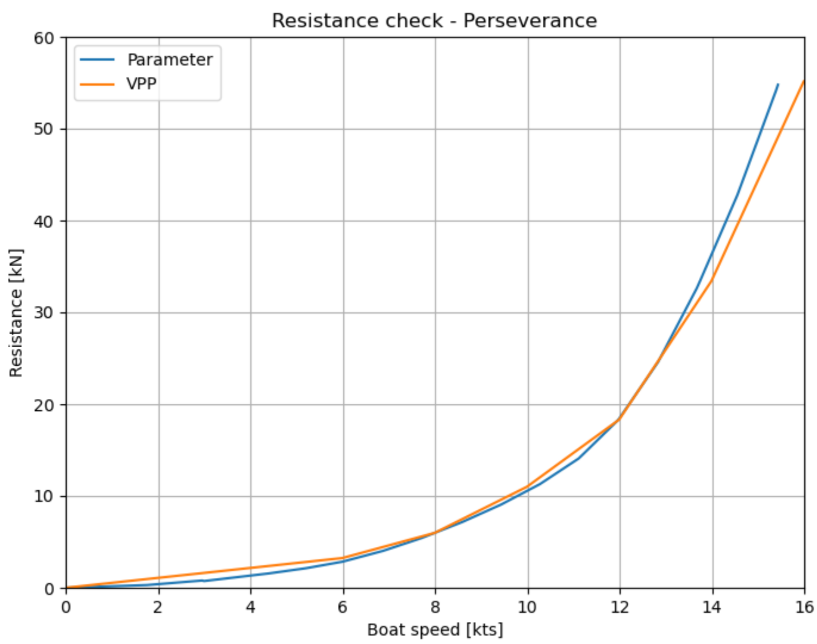


Figure 5.8: Comparison of resistance used for both approaches

5.3.2. Output check

The power output is checked by overlaying the results, similar to the resistance. Figure 5.9 shows the results of these overlaid outputs for Q1 middle, on-board *Perseverance*. All dots are the data points for the VPP, and the lines come from the methods calculations.

The identical points are the sailing speeds for the VPP (in red dots) and the parameters (in dark blue line). The VPP does calculate more points in the lower speed range. These are all the data points for upwind courses, which are generally slower than downwind. These lines have been lined up to check the differences by setting one variable as a constant.

The required speed for the VPP and parameter approach is not identical as this calculation uses different inputs and computations, such as the resistance. Nonetheless, the mean delta between these lines is still very similar and varies less than two percent, as is depicted by the grey and black dashed lines. The parameter approach always overestimates the resistance, meaning that the speed loss line lays above the line as determined by the VPP. The curves nearly line up at higher speeds, where generation is most likely used.

Some outliers stick out. For instance, the two black dots at about 8 kW output on the bottom left. These points represent the results from the VPP, where the yacht sails dead downwind. The speed decreases at this course, but the sailing speed during generation experiences relatively less decrease. These courses experience less resistance due to how the resistance for generation is calculated in the VPP.

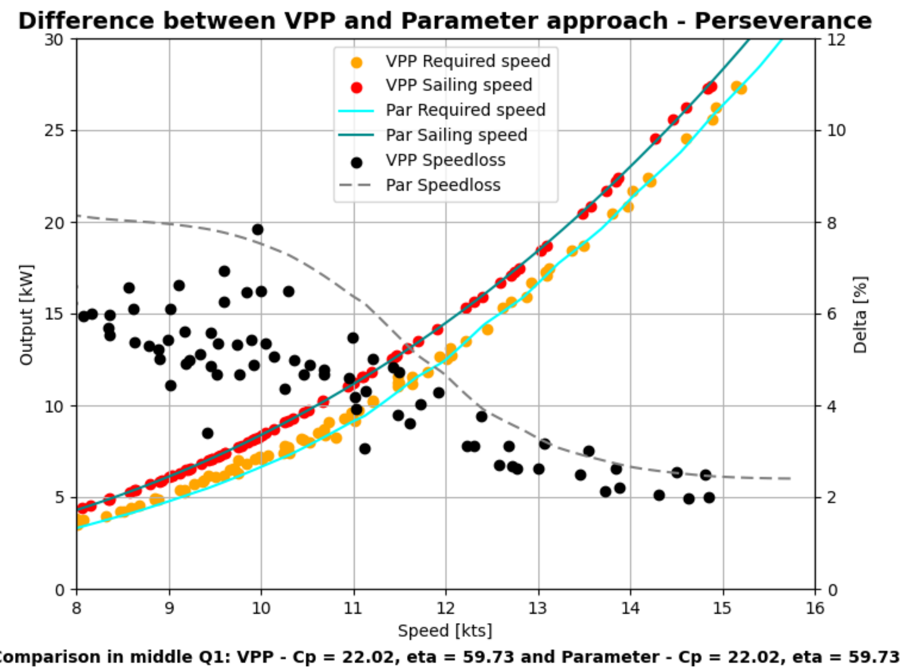


Figure 5.9: Comparison of power output used for both approaches

6

Block 1: Propeller size variation

The first part of assessing the physical impact on the yacht's design is determining the influence of the propeller. Block 1 assists with this by calculating the output for a varying propeller diameter. At different free sailing speeds, a curve is plotted in which the power coefficient setting is increased to max C_p. A relation between the output and speed loss is presented, providing insight into the best pitch setting for the propeller at a given speed. This process can also be executed for different propeller sizes by multiplying the propeller diameter with a multiplication factor. This chapter elaborates on the calculations performed in the block, present the results, and provide information on the executed inspections of the results.

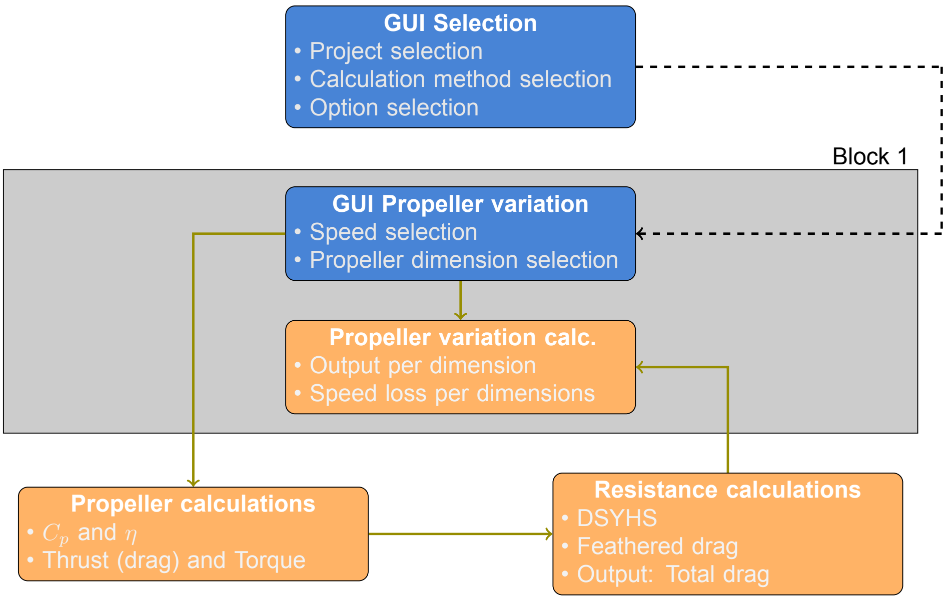


Figure 6.1: Overview of block 1

6.1. Block 1 calculations

The propeller variation accounts for two conditions: free sailing, where the energy output is zero, and generating, for all the points with energy output above zero. The resistance caused by hydro generation is calculated using 6.2. Resistance during free sailing is calculated using 6.1, but can also be determined using the formula for generation for the condition where the energy output is zero. These two formulas should produce the same answer for this zero condition.

$$R_{free} = R_{hull} + R_{feathered} \tag{6.1}$$

$$R_{generating} = R_{hull} + R_{prop,generation} + R_{structure} \tag{6.2}$$

This is checked by rewriting the formulas to the balance in 6.3.

$$R_{prop,feathered} = R_{prop,generation} + \frac{1}{2}R_{feathered} \tag{6.3}$$

$$\frac{1}{2}R_{feathered} = R_{prop,generation}$$

$$\frac{1}{2} \cdot C_d \cdot \frac{A_p}{A_d} \cdot \frac{A_e}{A_0} \neq \frac{C_p}{\eta_{generation}}$$

Due to the different calculation approaches and their simplifications, a dissimilarity is observed. The feathered resistance, for instance, follows a simplification whereby it is divided into two parts: 50% is assumed to originate from the feathered propeller, while the other 50% comes from the remaining shaft or thruster construction. This is a generalization that is not always true, as the distribution varies per specific construction.

If the resulting balance in 6.3 is assumed to be true, a minimum limit can be constructed for the $\frac{C_p}{\eta_{generation}}$ ratio. This lower limit is set at $\frac{C_p}{\eta} = 0.051$ for *Perseverance* using variables: $\frac{A_e}{A_0} = 0.4$, $\frac{A_p}{A_d} = 0.85$, and $C_d = 0.3$. For the B4-70 propeller, this limit is exceeded for all C_p under 5%. When assuming the feathered balance is correct, the data for the B4-70 cannot be used below this limit in the same equation.

Combining these assumptions leads to different outcomes for free sailing points using the two formulas. Therefore, the decision is made to construct the plots such that only the relevant parts are presented. The free-sailing point is determined using the feathered drag approach, and the next plotted step is the first of the three propeller settings using the generation approach. All data between these points is left out of the plot as these propeller settings will not be used for hydro generation, given that there are better and more efficient points to be used on the other side of the usable spectrum. Within the scope of this thesis, this makes for a sufficient representation of the results, as all desired data is provided reliably. However, it is recommended to analyze this discrepancy in the lower part of the plot for C_p values below 5% in further research to find a balance between the applied approaches.

6.2. Results of variation

When using this part of the method, a selection is made for the diameters and starting speeds. The vessel used for the results in this section is the sailing yacht *Perseverance*, as applied in the scenario. The selected propeller is the B4-70 with the original 0.9-meter diameter. This serves as the basis for the calculations. On this diameter, a multiplication factor is applied. The diameter is the only variable that is changed in this example.

The variation can be run for starting speeds of 8, 10, 12, 14, 16, and 18 knots. Points outside this range were deemed unrealistic for hydro generation, either because they were too low for usable power outputs or too high because the vessels within the method operating range could not reach them.

The different points on the x-axis depict the direct loss caused by a larger propeller in feathered mode. If the size increases, the speed decreases, and vice versa for a decreased propeller diameter. Additionally, the propeller variation depicts the energy output for different propeller settings. This helps with choosing a specific propeller if a predetermined minimal level of energy output is required. It also shows the benefits of selecting a lower C_p and thus a higher η in certain situations. At lower sailing speeds, the speed loss becomes apparent for an increase in C_p. Due to the lower speed loss, the output becomes relatively higher as speed applies to the third power. The actual produced energy could thus be higher for a lower C_p setting combined with a higher sailing speed.

The difference between the first and third quadrants is the maximum output. In figure 6.2, a 20% increase is visible. Higher energy output is combined with an increase in speed loss. At 10 knots starting speed, the loss is significantly more abundant for the third quadrant. The energy output increases if a higher C_p setting on the propeller is selected. However, this also increases resistance and thereby decreases sailing speed.

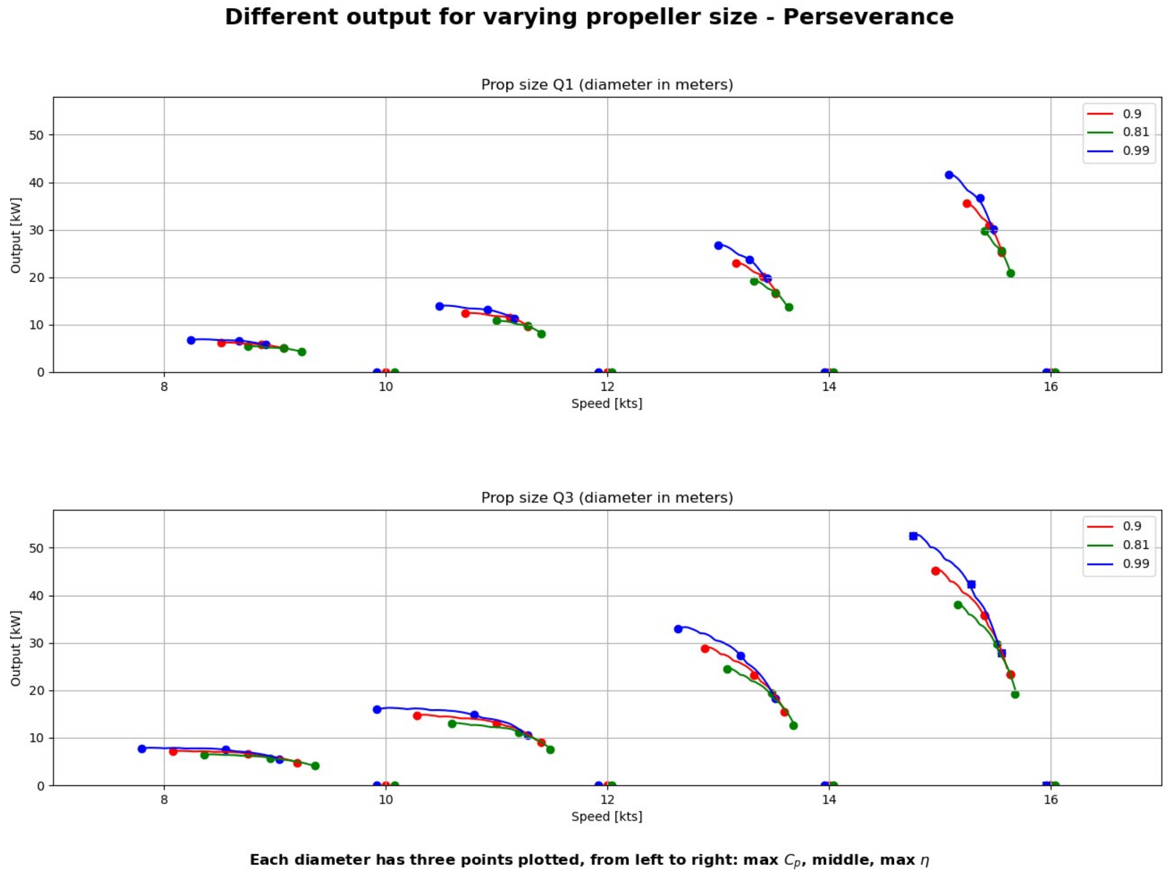


Figure 6.2: Propeller variation for *Perseverance*

Figure 6.3 is added to provide an example of an extreme increase in propeller diameter. This proves that increasing the propeller size to generate more energy is not always an option. The losses in sailing speed accumulate to 30%, with higher C_p settings in this specific example. The first setting can already lead to a 25% speed loss at lower sailing speeds. Additionally, it shows that in some situations, for instance, for a free sailing origin of 14 knots, the higher C_p results in lower energy output due to the speed loss. Information from this block depicts a part of the physical impact on the system. It is used to visualize the cost of a larger propeller diameter and indicate an optimal blade pitch setting.

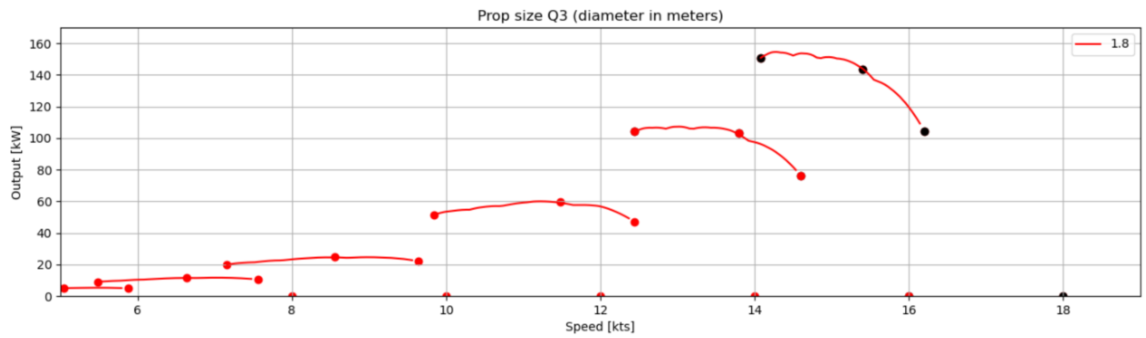


Figure 6.3: Extreme propeller increase for *Perseverance*

Increasing propeller diameter does not only provide benefits. It also increases resistance. This cost is doubled as the blade area is both considered in the generation resistance and the propeller structure resistance, as this structure also increases in size. Considering that speed is more important than size when it comes to hydro generation also indicates a limit for the feasibility of increasing the propeller diameter.

6.3. Calculation check

The result of the calculations is verified using previous parts of the method, such as the results presented in figure 5.6. If the line for the output of one pitch setting and diameter lines up with all the points of that pitch setting for the different speeds, the result is valid.

This is done in figure 6.4, for max C_p, the energy output lines in the third quadrant are plotted over the result of block 1 for the original propeller on *Perseverance*. All points line up for both lines, proving the consistency of the calculations.

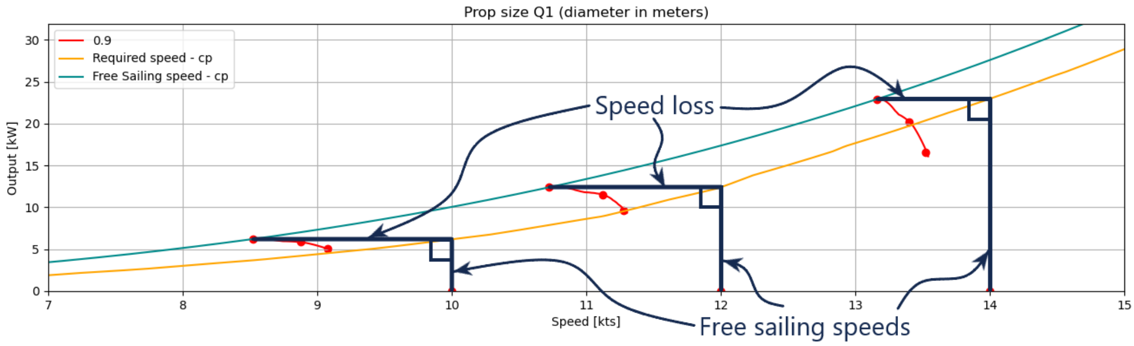


Figure 6.4: Check of the outcome of the propeller variation

A second and more thorough method of checking the results is performing a reverse hand calculation. Using the results for the selected point of max C_p in the first quadrant, the following data is used:

- Speed = 13.16 kts
- Original speed = 14 kts
- C_p = 26.4%
- η = 48.0%

The free-sailing point at 14 kts, using 6.1, and the generating point at 13.16 with max C_p, using 6.2, should therefore have a similar resistance. With resistance calculations from the DSYHS as in section 5.1.2, the feathered resistance as in section 5.1.3, and the generation resistance using formula 6.4, the following total resistances 6.5 and 6.6 are determined.

$$P_p = \frac{\frac{1}{2} \cdot \rho \cdot V_a^3 \cdot Aprop \cdot C_p}{\eta} \qquad \text{[kW]} \tag{6.4}$$

$$R_{generation} = \frac{P_p}{V_a}$$

$$R_{free,14kts} = R_{hull} + R_{feathered} = 36.262 + 2.719 = 38.98 \qquad \text{[kN]} \tag{6.5}$$

$$R_{gen,13.16kts} = R_{hull} + R_{prop,gen} + \frac{1}{2} R_{feathered} = 27.635 + 8.184 + 1.204 = 37.02 \qquad \text{[kN]} \tag{6.6}$$

A 2 kN or 5% difference between the resistances is observed. This is within an acceptable error range. An explanation for this difference is found in the simplification process of the resistance calculation, as the driving force remains near constant. The performed calculation is not an iterative process that aims to find a balance. Instead, it performs an educated guess using a simplified energy balance that only considers the sum of the forces in the x direction. This will also make the answer less precise, considering that the driving force is unlikely to remain unchanged for both situations. Additionally, the generalization of always using a factor of $\frac{1}{2}$ for the remaining drag by the shaft (or thruster) will lead to inconsistencies.

7

Block 2: Generator size prediction

After determining the propeller size, the next part of the system to assess is the physical size of the generator that corresponds with the propeller's generated energy output. This prediction is performed in the second block of the method. The second block is the shortest and a separate calculation, as the overview 7.1 shows. The only input it uses is the power output of the method basis. The estimation is more relevant when a separate solution for hydro generation is implemented instead of an integrated method. Nearly all yachts generate with the same system as the propulsion system. On these vessels, a hybrid solution is applied. This means that there is already an electric machine driving the shaft line.

This chapter explains how a prediction was made for the size of the electric machine if it was only a generator. So, it is not considered if the electric machine also acts as a motor for propulsion. The powers a propulsion motor provides are higher than those extracted during generation. This would thus be the design driver for an integrated system instead of the generator design. First, the calculations are presented along with a verification. Then, the results from this block are provided.

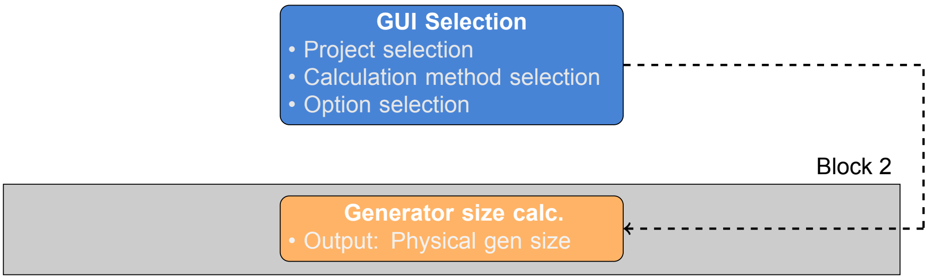


Figure 7.1: Overview of block 2

7.1. Calculations and check

Two methods were tested to determine the generator size: a trendline analysis of a database and an estimation method derived from the literature. The two different approaches also serve as a check. If both calculations provide the same result, that outcome is considered correct.

The trendline analysis applies a polyfit, a fitted line, a fitted curve, and an exponential fit to a database. Several lines were selected due to the nature of the database. The database is two combined catalogs for electric motors suitable for marine applications by ABB (2021) and Hoyer Motors (2020). The data reveals lines at different steps over the size axis. This is caused by manufacturers applying the same housing to multiple generators. None of the curves fit perfectly through the data set. The exponential fit works well near the origin, yet higher values are underestimated. The fitted line has the worst fit, and the polynomial regression and fitted quadratic curve follow the data well but dip slightly toward the end. An overview is provided in figure 7.2.

Another approach is derived from literature. Stapersma and de Vos (2015) describe a method to generically size the main dimensions of primary equipment in marine applications. This includes the sizing of an electric machine. The sizing is based on the machine's core. For the electric machine, the

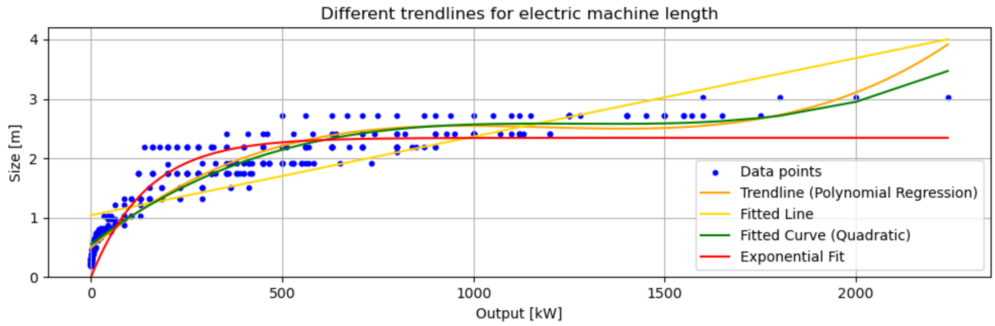


Figure 7.2: Different trendlines through the data set to determine the length of the electric machine

sizing is based on the rotor. The length of the rotor is determined using formula 7.1, with power P in watts, a shape factor λ, rotation speed n, and the mean shear stress τ_{EM}.

$$l_r = \sqrt{\frac{\lambda_r \cdot P}{\pi \cdot \tau_{EM} \cdot n}} \qquad \text{[m]} \tag{7.1}$$

The result is multiplied with polynomial factors (a_0 and a_1) to determine the length of the machine. The width and height can also be calculated using a similar approach or the shape factor.

$$l_{EM} = a_0 + a_1 \cdot l_r \qquad \text{[m]} \tag{7.2}$$

7.2. Calculation results

Figure 7.3 compares the lines. The method by Stapersma and de Vos (2015) was selected for further use in the design method, as this line fit well through the assembled data set while being designed using another set. This makes it the most verified option. It is challenging to check the method with actual examples, as this approach determines the size of a generator instead of a propulsion motor. All vessels with available data are designed with an electric machine that acts as a motor. These are larger and deliver more power. Both data sets consist of induction motors as these are also the type used in the method by Stapersma and de Vos (2015). However, it should be noted that permanent magnet motors can be used for the same purpose. Permanent magnet motors are not considered in this thesis as the method by Stapersma and de Vos (2015) was selected.

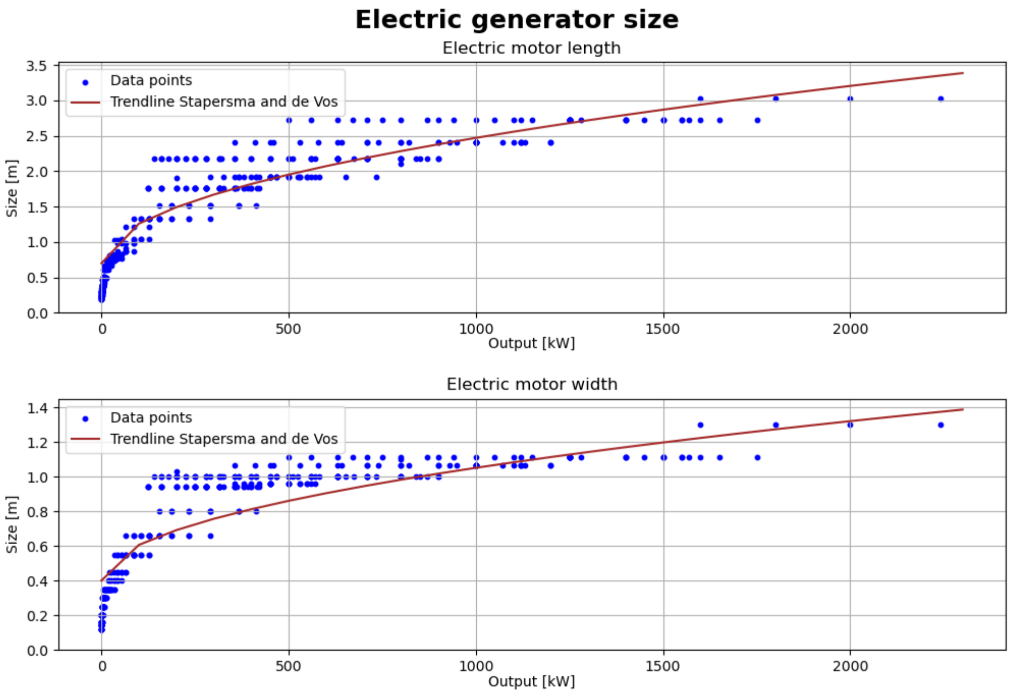


Figure 7.3: Electric generator size prediction

8

Block 3: Energy balance

The third and final block of the method fills in the blanks regarding GA, emissions, and the yacht's usage. The assessment of the physical impact is completed with a determination of the battery size. The fuel savings and resulting emission savings are determined. The influence of the sailing region, and thus yacht usage, is considered.

This final block is used to assess the scenario that shows the use of the method. In this block, three calculations are performed: the energy demand for the hotel load and the estimated generation output of a yacht. The sum of these shows the energy balance on board a sailing yacht. Some first results are presented with a verification at the end of the chapter. A more complete assessment of the results will follow with the scenario results in the next chapter.

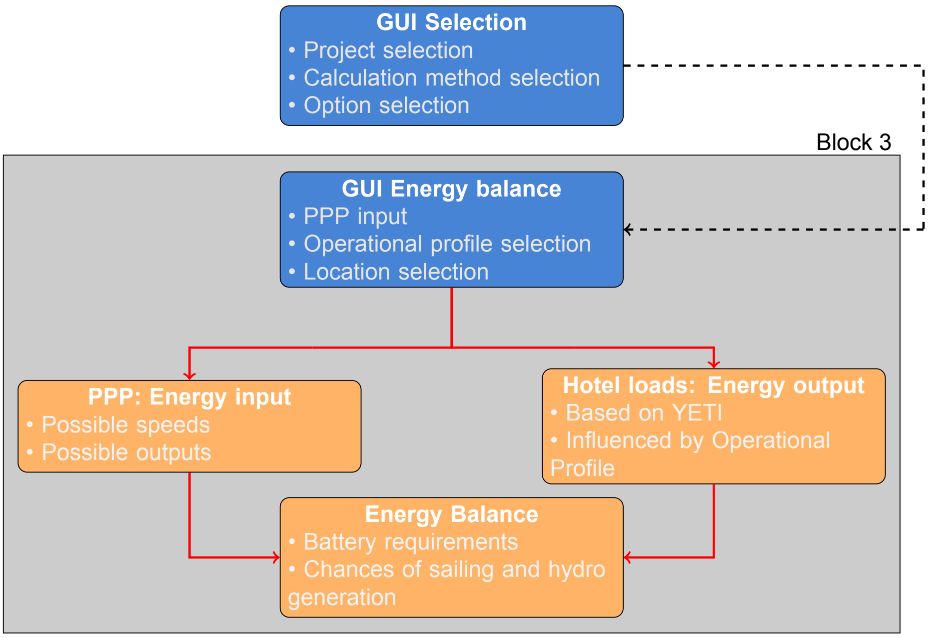


Figure 8.1: Overview of block 3

8.1. Hotel load calculations

The hotel load calculations are created using the equations based on correlations from YETI (van Eesteren Barros, 2022). Appendix A provides a complete list of the used equations. By multiplying each group with a specific ratio for when the yacht is on anchor, in harbor, or sailing, an estimation of the total average load over 24 hours is created.

The values calculated via the YETI approach were deemed to be high, especially for sailing yachts. To correct this, an additional multiplication factor is introduced based on the waterline length of the sailing yacht. As a very accurate estimate of the hotel load was deemed to be beyond the scope of this thesis, a simple approach was taken to determine this factor. A second-degree polynomial was drawn through three data points. The hotel load was known for a 30, 60, and 100-meter yacht, resulting in a multiplication factor between 0.33 and 0.5 to estimate a more accurate hotel load using YETI. Combined with the operational profile, the average load estimations are made on how much energy is consumed.

8.2. Performance prediction program

The Performance Prediction Program (PPP) created for this research is a significantly simplified version of a Velocity Prediction Program (VPP) applied at DNA. A VPP iteratively finds a balance between all the forces on the hull and rig. The result is an achievable speed for various wind speeds and directions. The PPP simplifies the calculation of the sailing speed for different wind speeds and true wind angles. The downside of this approach is that the results are less accurate. The upside is that the calculation time and number of required inputs are reduced. This makes the PPP perfect to be used in the early stages of design, the original goal of the method.

The most predominant change is that only a balance is sought in the X direction, meaning that the sum of all forces in the X direction equals zero. The force balance in Y and Z direction and all moments are disregarded to simplify the calculations. The balance in the X direction is simplified by evaluating resistance in flat water and without heel. This results in formulas 8.1 and 8.2 for free sailing and hydro generation, respectively.

$$F_{driving} = R_{hull} + R_{side} + R_{feathered} \qquad [\mathrm{N}] \tag{8.1}$$

$$F_{driving} = R_{hull} + R_{side} + R_{prop,generation} + R_{structure} \qquad [\mathrm{N}] \tag{8.2}$$

8.2.1. Input

Several inputs are required for the PPP to work. Some of these inputs, including water and air density and the mast coefficient, are the same for all vessels. Other variables such as propeller efficiency, wake, air and keel draft, and the sail area are ship dependent.

To be able to determine the power produced by the sails, sail coefficients have been established. These coefficients are only representative of an upwind sail set. A future addition for this PPP could be a downwind sail set with corresponding sail coefficients. The coefficients have been derived using a trendline analysis at DNA. The data set includes various setups of Dynarigs and more traditional upwind sail sets from DNA design *Hetairos*. To use one data set for all sailing yachts is a significant simplification. A future upgrade for the method would be to split this into different data sets for various rigs and allow the user to select one.

Another simplification for the input is deciding when to reef the sails. Optimally, this would be done by creating a balance in the heel of the yacht. As the method does not aim to find a balance in the heel, the reefing is done based on the wind speed. For the sake of simplicity, the yacht sails with a complete sail set until eighteen knots and has zero sail area at forty knots. The sail area is linearly reefed away between those points. A visualization of the reefing process is provided in figure 8.2 a more realistic version of this would be a step-wise function, as sails can usually only be reefed in predefined steps. The wind data is retrieved from calculations on other projects by DNA, as explained in section 4.1. The data sets have been created using routing software where a vessel sails a predetermined route multiple times. Then, the average of the sum is taken of all wind speed and angle occurrences.

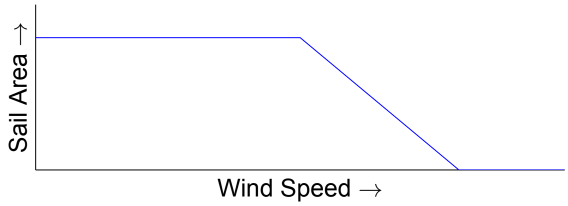


Figure 8.2: Visualization of reefing, the start and stop of reefing can be varied

8.2.2. Calculations

The following calculations are performed for each of the propeller settings. A loop is formed for speed steps, similar to the applied approach during the method's basis. The resistances are copied from earlier calculations. A visualisation of the forces is presented in figure 8.3.

1. First, the wind triangle is determined with the principles of the vertical wind profile (Spera & Richards, 1979):

$$TWS_x = \cos(TWA) \cdot TWS \cdot (t_{air} \cdot C_{mast})^{0.1} + V_{ship} \qquad \text{[m/s]} \tag{8.3}$$

$$TWS_y = \sin(TWA) \cdot TWS \cdot (t_{air} \cdot C_{mast})^{0.1} \qquad \text{[m/s]} \tag{8.4}$$

   The exponent of 0.1 represents a neutral atmospheric boundary layer.
2. Using the X and Y, the apparent wind angle is calculated:

$$AWA = \arctan\left(\frac{TWS_y}{TWS_x}\right) \qquad \text{[deg]} \tag{8.5}$$

3. As well as the wind speed:

$$AWS = \sqrt{TWS_y^2 + TWS_x^2} \qquad \text{[m/s]} \tag{8.6}$$

4. The dynamic pressure is calculated with the known wind speed:

$$p_{dyn} = 0.5 \cdot \rho_{air} \cdot AWS \cdot \left(\frac{1.854}{3.6}\right)^2 \qquad \text{[Pa]} \tag{8.7}$$

5. The sail area and dynamic pressure are combined into the gross driving force from the sails:

$$F_{driving} = AWA \cdot p_{dyn} \cdot A_{sail} \qquad \text{[N]} \tag{8.8}$$

6. Next, the resistance due to the side force is calculated:

$$F_{side} = TWA \cdot p_{dyn} \cdot A_{sail} \qquad \text{[N]} \tag{8.9}$$

7. And the resistance caused by this side force:

$$F_{side\ resistance} = \frac{F_{side}^2}{\pi \cdot \rho \cdot (V_s \cdot \frac{1.854}{3.6})^2 \cdot (t_{max} \cdot 0.8)^2} \qquad \text{[N]} \tag{8.10}$$

8. Using the hull and propeller resistance from previous calculations, the driving force, and the resistance caused by the side force, a balance is sought in the X direction:

$$F_{balance} = F_{driving} - F_{side\ resistance} - F_{hull} - F_{propeller} \qquad \text{[N]} \tag{8.11}$$

Due to the simplifications, the previously calculated $F_{balance}$ is not zero. This information is used to determine the generated system output per wind speed. The system is balanced when $F_{balance}$ equals zero, and the yacht will not accelerate. This occurrence is unlikely due to the relatively large step size for wind speed and angle. If F is negative, the sails do not produce enough power to generate at this sailing speed, resulting in deceleration. If $F_{balance}$ is positive, the yacht is speeding up besides generating energy.

A data set is created by looping for increasing Froude numbers. The number of positive values for F decreases with increasing speeds. All data sets are stacked, starting at the lowest sailing speed. This overwrites the spot in the middle of the scatter where the acceleration is significant, and a higher energy output could occur. The sailing speed increases in 'rings' as does the system's energy output.

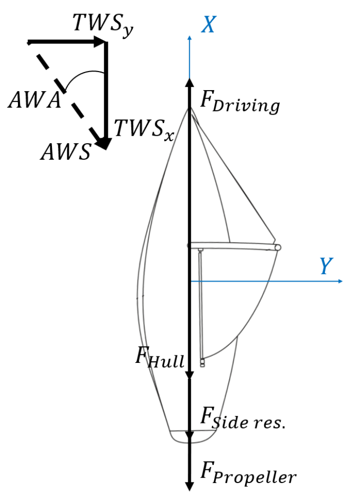


Figure 8.3: Balance in X direction

8.2.3. Error

An error occurs in the calculation due to the chosen approach of a simplified balance instead of iterating until one is reached. The created balance in formula 8.1 for free sailing is not always zero. Some residual forces also need to be considered as an error.

Eliminating this error would require an iterative calculation and is thus impossible for this thesis due to the selected calculation approach. Instead, a limit is implemented into the PPP to counteract this error. Higher forces cause higher errors, as shown in figure 8.4. So, to limit the effect, all results above a vessel speed of a 0.45 Froude number are deemed incorrect and replaced with data corresponding to a 0.45 Froude number.

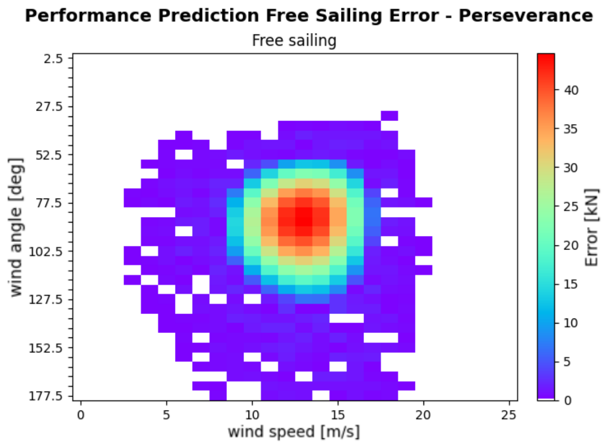


Figure 8.4: Error in balance

8.2.4. Results

Three choices are made to increase the usability of the results. Additionally, they help with establishing the energy balance. The first decision is that yachts traveling at 0.8 times the transit speed will turn on the engine and either start motor sailing or fully motoring. The second decision is that these yachts will only begin to hydro-generate when there is enough excess energy. So, free sailing will stop, and generation will only start when 1.2 times the transit speed is reached. The final decision is to maximize generation when possible, meaning that optimal performance is maximum energy output. So, the highest energy output will always be chosen over a higher sailing speed, but only if 1.2 times the transit speed is reached.

These assumptions combined result in two sets (first and third quadrant) of scatters, one for energy output and one for the corresponding sailing speed. In figure 8.5, the highest power production is selected per wind speed and direction. The white area indicates the zones where the yacht cannot sail either due to insufficient wind, a disadvantageous wind direction, or because the wind speed is too high and the sails are fully down. The zone is restricted by the imposed 0.8 times transit speed limit, making it identical for the first and third quadrants. The grey area is the free sailing zone between the set limits of 0.8 and 1.2 times the transit speed. This zone is nearly identical as the higher efficiency for the first quadrant allows generation to start slightly earlier for some wind conditions.

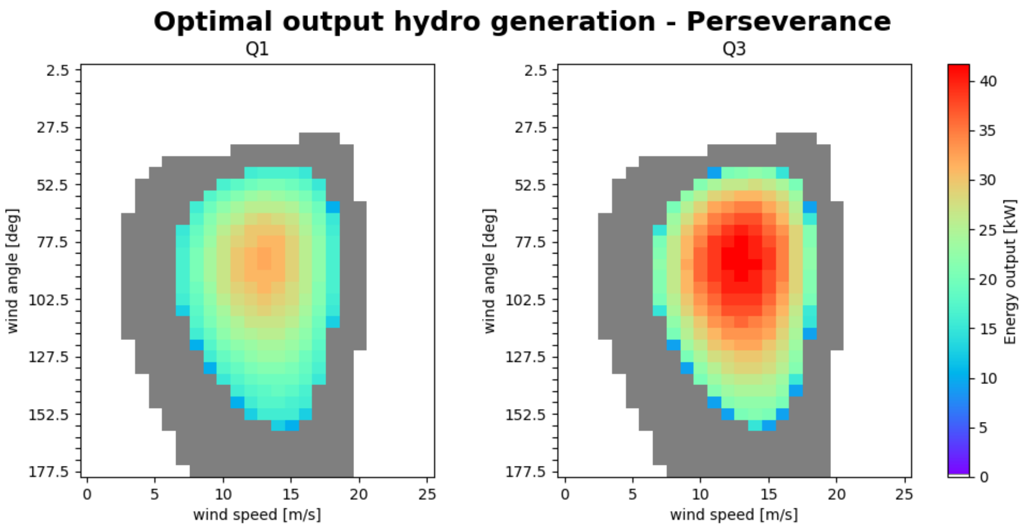


Figure 8.5: Optimal energy output for the first and third quadrant

The most significant differences occur in the final zone, the generation zone. Here, the generated energy output is significantly lower for the first quadrant. However, as is proven by figure 8.6, maximum speed is earlier achieved. This is only a 1.25% difference in the overall compared speed difference. Negligible compared with the energy output gained in the third quadrant, which is, on average, 25.43%. The average generated power is determined by applying the chance of each wind condition for a specific route.

The figures are most accurate in the upper half, where the yacht is sailing upwind. The data for the sails is that for upwind sails. When sailing downwind, there would be more energy generation with higher wind speeds. So, in the bottom right of each figure. Additionally, the yacht can keep sailing longer in heavy weather with a small set of sails. This means that the white border on the right of each figure becomes smaller. This is not considered in this method due to the considerable generalization.

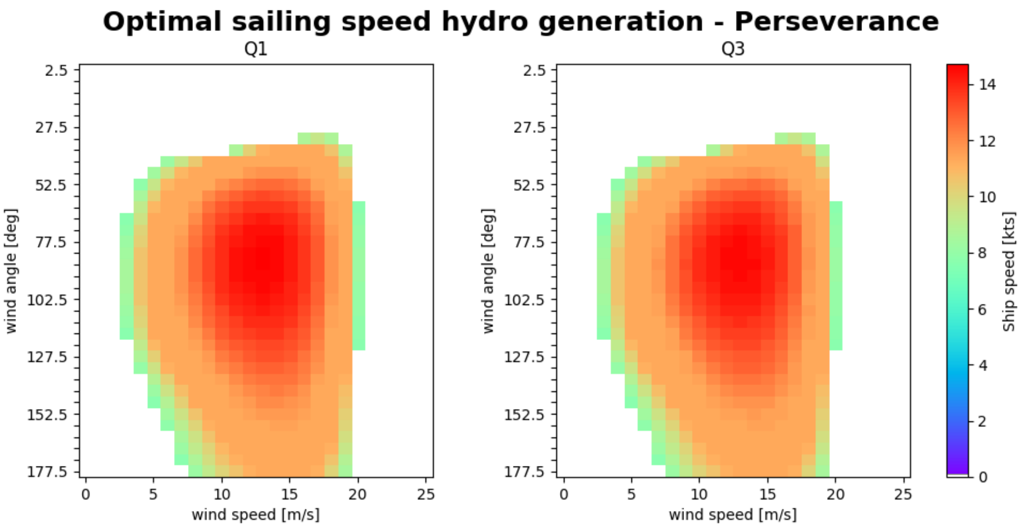


Figure 8.6: The corresponding sailing speed for the optimal energy output

The propeller pitch changes quickly to the maximum C_p setting, if not instantly, when hydro generation is engaged. This delivers the most power at the higher speeds where generation is started. This is caused by the assumption that an optimal output is the maximum energy. If hydro generation is engaged at lower sailing speeds, the propeller pitch remains at a maximum efficiency setting longer. This is caused by the sailing speed and energy output loss for higher energy output settings at lower sailing speeds, as shown in figure 6.2.

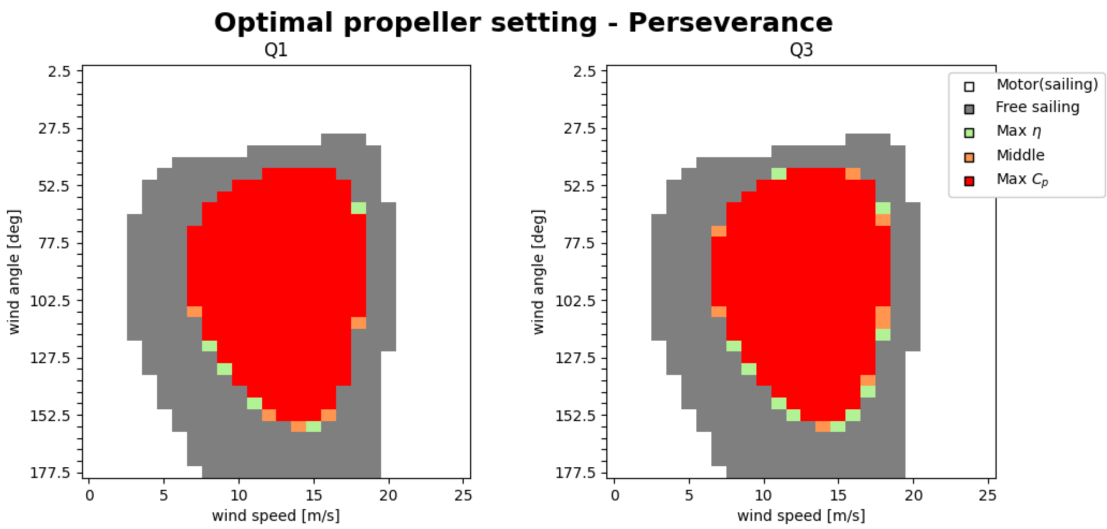


Figure 8.7: The corresponding propeller settings for the optimal energy output

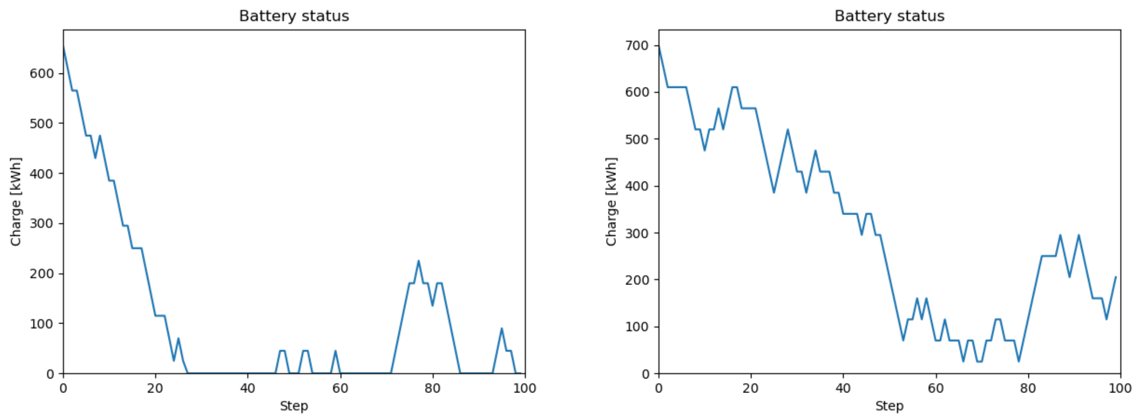
8.3. Energy balance

The information displayed in figure 8.5 shows the energy output for all possible wind direction and speed combinations. By multiplying this data by the probability of these wind options, an estimation is formed for the chance of hydro generation. Such a wind probability matrix is based on collected data over specific sailing routes (IMO, 2021). The result is the chance of motoring (event A), free sailing (event B), and generating (event C) for a particular traveled route. An example distribution could be 30% motoring, 50% free sailing, and 20% hydro generating. Considering the scenario, the following event descriptions have been selected:

- Event A does not cost or produce electrical energy for the battery balance. So, the battery charge remains constant.
- Event B only costs energy as power is consumed for the hotel load, but no energy is produced. So, the battery charge decreases.
- Event C costs energy with the hotel load but also produces energy with hydro generation. The battery charge will increase when the hydro generation input exceeds the hotel load.

These descriptions are specific to the selected scenario and could be altered to fit a distinct situation or trip for a yacht. Additionally, it is assumed that the vessel departs regardless of the condition and sails straight to its destination regardless of the weather. As well as a fully charged battery upon departure.

Using the chances for an event to occur, a route is simulated using a randomizing function. It sets up a series of events where a new event occurs every three hours of the trip. So, one step lasts three hours. An overview is created for the battery charge by monitoring the energy balance over the entire trip. The trip was successful when the charge state did not reach zero. Figure 8.8 provides an example of such a trip that was a success and one that was a failure. For this example, only the battery size was changed. This is considered one of the main influences on the success rate.



(a) Unsuccessful crossing, battery not sufficient **(b)** Successful crossing, with a larger battery size

Figure 8.8: Battery charge for two trips

The success of one trip does not prove that this is always the case. By simulating enough trips, an overall success rate is determined. The total distribution of the events now returns to its original distribution as derived from the wind matrix, as shown in figure 8.10. Within this simulation, there might be trips where almost the entire distance could be sailed. And there might also be trips with no sailing at all. The importance of the sequence of events is eliminated by completing enough trips.

When a trip is unsuccessful, the number of hours the battery was empty and thus a backup generator was run is saved. A distribution is formed for each simulation for all the backup generator hours per trip. Figure 8.9 is an example of such a distribution. It is a collection of 100,000 transits, crossing the Atlantic with a random sailing yacht for the example distribution (30-50-20) in 300 hours. The sailing yacht has a hotel load of 15 kW, an average hydro generation capacity of 30 kW, and a 700 kWh battery. The total success rate for a complete battery crossing is 1.5%, and 94 hours of diesel generator running is needed on average. In this thesis, only the physical size, weight, and size of the energy storage are considered for the batteries. Assuming all other variables and requirements such as voltage, charge and discharge rate, life cycles, and capacity are sufficient for the use case in the scenario. The battery density is based on phosphate batteries, as defined by Verma and Kumar (2021), with a size density of 182 $\frac{kWh}{m^3}$ and a weight density of 0.133 $\frac{kWh}{kg}$.

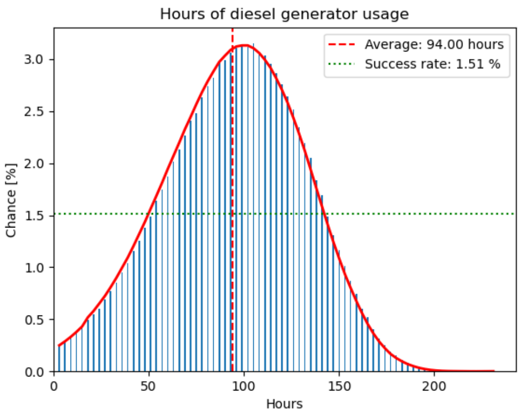


Figure 8.9: The hours of generator usage over several crossings

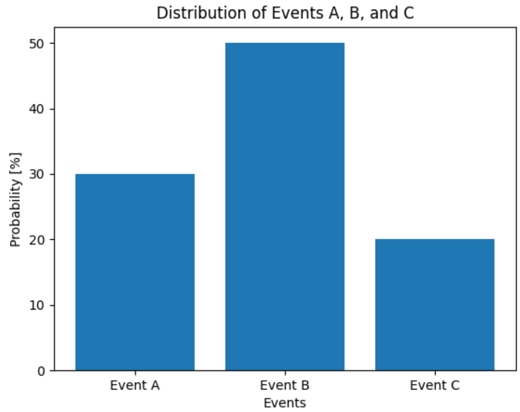
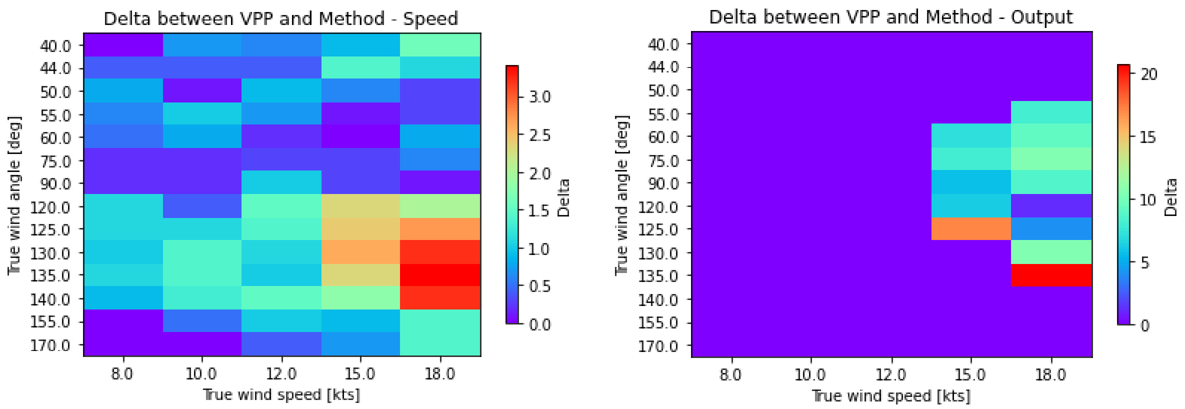


Figure 8.10: Event distribution

8.4. Check

To verify these results, data from an existing yacht is required. This is partially done in the scenario. The hotel load has been altered to fit genuine sailing yachts better with the factor, as before, it did not align with existing data.

The data from the PPP is checked using VPP data for an existing yacht during generation. The average energy output cannot be compared as different inputs are used for both the VPP and design method. By filtering both approaches, a comparison is made. For the VPP, the same assumptions were made as for the design method. No generation would occur under 1.2 times the transit speed, and at 0.8 times the transit speed, the yacht begins to motor sail. From the method, only a slice of the data was used for the wind speeds and wind angles determined in the VPP as presented in figure 8.11.



(a) Speed delta in kts

(b) Output delta in kW

Figure 8.11: Deltas between VPP and Method

Figure 8.11a, which depicts the difference in speeds during generation and free sailing, has deltas that reach as high as 3 knots. However, these points are for the downwind part of the data at wind angles greater than 90 degrees. Here, the VPP will have switched to another, better suitable, sail set for these wind directions. The method cannot do this and is thus likely underpowered at these wind angles. The upwind section of the data set has lower deltas in general. The method's selected sail set is better suited for these angles. The upwind data from the design method is more reliable as it deviates less from the more complete VPP calculations.

Figure 8.11b, which depicts the difference in energy output during generation and the point of activation for hydro generation, has significantly larger deltas. Partially, because the activation point is very similar but not exact, the two points of around 15 and 20 kW deltas are points where the VPP has not activated yet while the method has. All values equal to zero show the points where the VPP and method concur. These high points are in the downwind part of the plot, where the speed delta is also the highest. The varying inputs used for the VPP and method explain the difference in energy output. The VPP can only work with one propeller setting while the design method optimizes to find the highest energy output. The result is that all upwind energy outputs are estimated higher by the design method, and all downwind ones are estimated higher by the VPP. These comparisons are made for *Perseverance* and are thus not universal deltas. However, the conclusions that are drawn from it are universal.

9 Scenario results

Following the conclusion of all the separate calculations in the method, as performed in chapters 5 till 8, the scenario described in chapter 4 is analyzed. This analysis combines the results of different parts of the method, providing a conclusion on the scenario's four areas of interest. Each of these areas is linked to a specific part of the method.

1. A prognosis for the hydro generation systems energy output.
    - Propeller operating points → Basis
    - Produced energy → Basis
2. The physical impact on the system.
    - Propeller size variation → Block 1
    - Generator size → Block 2
    - Battery size → Block 3
3. The impact on fuel consumption and emissions.
    - Fuel saving → Block 3
4. The impact of sailing regions and yacht usage.
    - Sailing region → Block 3

The goal of this chapter is to confirm the usefulness of the design method. If it can be used to analyze the four areas of interest, the third sub-question: *How can a selection method be formed to determine which hydro generation configuration would suit a specific sailing yacht (or refit) best?* is considered to be answered.

The final sub-question: *To what extent does the implementation of hydro generation influence sailing yacht design, and which choices indicate the implementation limit?* is answered in this chapter by looking into the design parameters. What parameters influence the success rate of a crossing, and which point is a limit reached? Parameters such as sail area, propeller diameter, and battery size are considered. A switch from the first to the third quadrant is also considered. The analysis is performed per yacht for *Perseverance* and *Zero*. The parameters used in the method are listed in appendix E. These serve as the input for the calculation method. The chapter concludes with a comparison of the two results.

9.1. Perseverance

Perseverance is the yacht used for developing the design method for this thesis. *Perseverance* is a composite sloop with a 31-meter waterline length. The existing yacht, with little real-life data, is used to verify the method to the best extent possible. First, the design data is used to look into the success rate of the scenario. Once completed, this data is varied to look into the limits of hydro generation. With the average trip speed of 10.19 knots for *Perseverance*, the trip duration for the 3200 nautical miles is estimated at 315 hours. The hotel load used under sail averages 15.15 kWh over 24 hours. It is considered as a constant average load.

9.1.1. Prognosis of the hydro generation systems energy output

The energy generation prognosis performed in the method's basis consists of two parts: a determination of the propeller operating points using the propeller characteristics and an estimate of the produced energy by the propeller. An explanation of the executed calculations is provided in section 5.1.

Propeller operating points

Perseverance will generate in the first quadrant with the B4-70 selected as the propeller used for generation. Following the method in section 5.1.1, three pitch settings selected:

1. Max C_p - $C_p = 26.40$ % and $\eta = 48.01$ %
2. Middle - $C_p = 23.75$ % and $\eta = 54.02$ %
3. Max η - $C_p = 17.88$ % and $\eta = 64.22$ %

The three points are visualized in figure 9.1. The maximum efficiency point and the middle point share a $\frac{P}{D}$ value of 1.2, and the C_p point is located on the curve $\frac{P}{D}$ = 1.

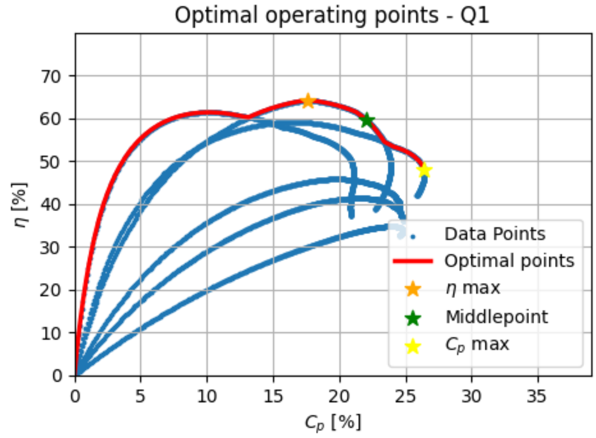


Figure 9.1: Available operating points in Q1 for the B4-70

Produced energy

The energy production potential of each point is calculated. The speed loss caused by hydro generation is also determined using the calculations presented in section 5.1. The results are plotted in one figure per operating point that shows both the energy output and associated loss.

The blue curves plotted in figure 9.2 show the energy output for the sailed speed. The yellow line shows the extra sailing speed that would have to be sailed to reach the desired energy output. The dashed line represents the speed loss per speed at the selected propeller operating point. The loss is lower for higher propeller operating efficiencies. But the energy output decreases as well. A balance is sought within the process to minimize speed loss and maximize energy output. For some speeds, switching to a higher propeller efficiency setting becomes beneficial. The speed loss decreases, and the relative energy output increases. For *Perseverance*, this occurs at sailing speeds below 12 knots.

Figure 9.3 shows this balance. The points on the x-axis are the free sailing speeds, the speed at which the yacht would sail without generation. If the generator is turned on, it will first be set to the max η point, the first point on each line starting at the free sailing speed. Next, the middle point is reached, and each line ends at the max C_p point on the left side of each line. For free sailing speeds below 12 knots, the change in output is insignificant for the final two points. From 10 knots on, the difference between all three points is negligible. However, the speed loss is significant. At

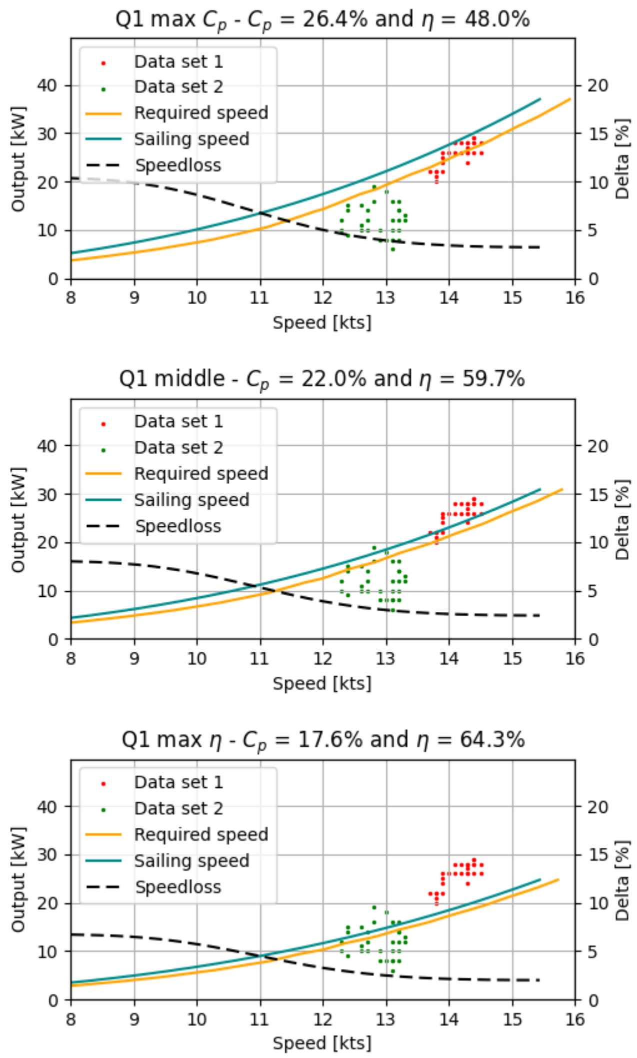


Figure 9.2: Maximum energy output for three settings

these speeds, it is beneficial to set the propeller to a higher efficiency and sail faster. If the propeller size increases, the effect could even reach the point where the output decreases for a higher C_p setting purely due to the extra loss in speed.

The desire for hydro generation is unlikely at lower speeds as the loss of sailing speed can reach 10% or more. Two limits were introduced to prevent this. Firstly, a lower limit for hydro generation at 120% transit speed. Secondly, a lower limit for free sailing at 80%. For *Perseverance*, these limits are determined using the waterline length, as previously mentioned in section 2.1.2.

- 80% of transit: fn = 0.22 [-] and v = 7.64 [kts]
- 100% of transit: fn = 0.28 [-] and v = 9.55 [kts]
- 120% of transit: fn = 0.33 [-] and v = 11.46 [kts]

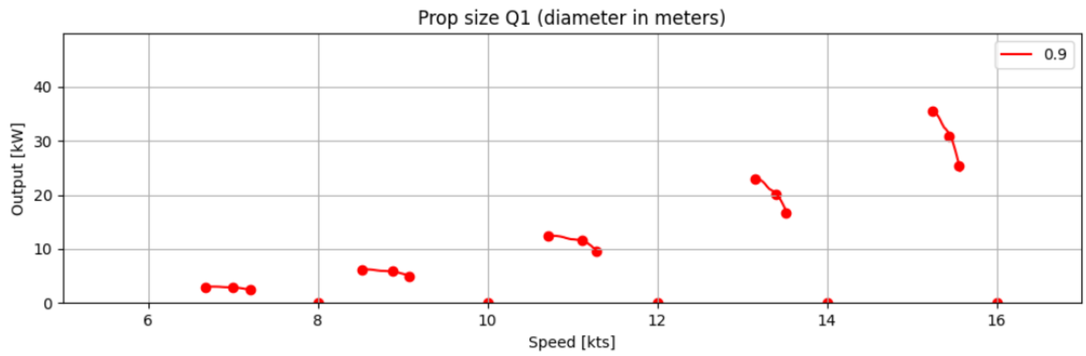


Figure 9.3: Balance propeller settings *Perseverance*

The only existing data on the output of the hydro generating system on board *Perseverance* are two data sets only displaying a small number of points recorded in 20 seconds. For comparison, the operating points have been plotted over the calculated data in figure 9.2. The conditions in which these tests were conducted are not known. The first data set, recorded at 13.5 to 14.5 knots, is less varied and shows all points below the maximum energy output line. As this line represents the absolute maximum, all data should be below it. The second data set suits the middle propeller setting better. It is a reasonable assumption that the C_p setting would increase for higher sailing speeds. Therefore, the data set for higher sailing speeds fits a higher C_p.

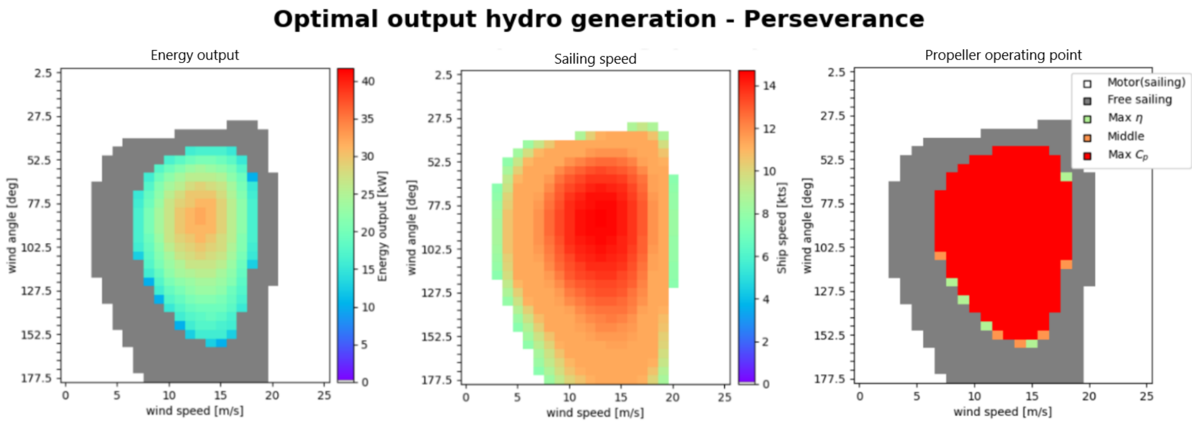


Figure 9.4: Output and speed for *Perseverance* as built

A prediction is made using a PPP, as described in section 8.2, of the possible output and combined speed for all wind speeds and directions. This gives a better idea of the balance between output gain and speed loss. This PPP also adds the possibility of combining the output data with wind data to determine the success rate for the scenario. The results of this PPP are displayed in figure 9.4, including the free sailing area and motor(sailing) boundary. The highest output is achieved when sailing with 90 degrees true wind a wind speed of 12 to 16 m/s. So, if there is wind data that also has a high occurrence of this wind, the output will increase. The average energy output when hydro generating, for the wind data in the scenario, is 19.25 kW

9.1.2. Physical impact on the system

The physical impact of hydro generation on a yacht's design is derived from each of the three parts of the system. The propeller is the turbine, the generator is the converter, and the batteries are the storage system. With *Perseverance*, the sizes of these parts are already known. The calculations are checked using these known sizes. Additionally, a variation study is completed to determine the impact of component sizes on the success rate of the scenario and the limits.

Propeller

For *Perseverance*, the propeller diameter is 0.9 meters, which becomes an input value for the method. The propeller is a controllable pitch propeller designed from a propulsion perspective and used for generation in the first quadrant. For this scenario, a B4-70 propeller is selected.

A variation of the propeller size is completed using the method as described in chapter 6 to determine the effect of a 10 and 20 percent increase. Any larger is deemed unrealistic without significant design changes. It is plotted in figure 9.5, detailing the larger output and the added speed loss.

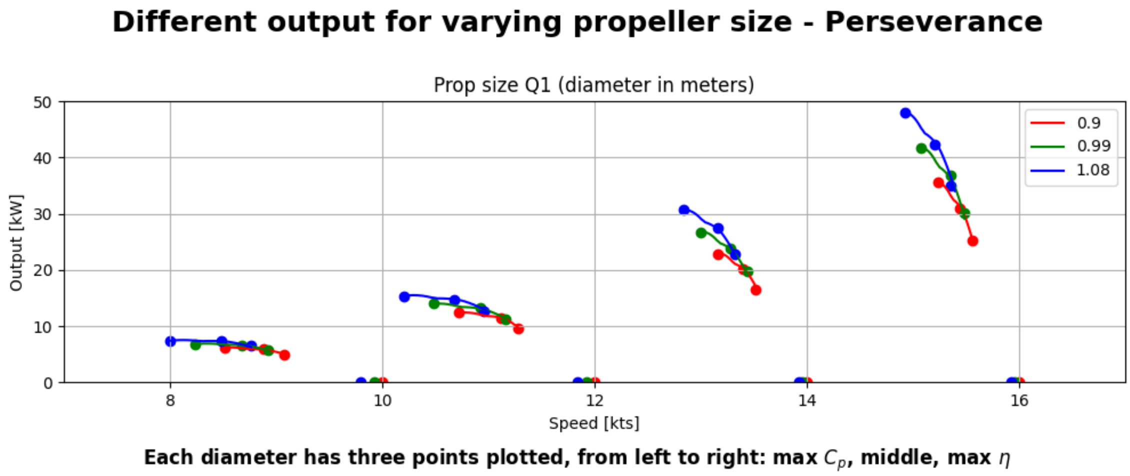


Figure 9.5: Propeller variation for *Perseverance*

Generator

The generator on board *Perseverance* is the same electric machine used for propulsion. Therefore, the estimated size does not correspond with the method's estimation as performed in chapter 7. The method approximates a generator with a 1.2-meter length and 0.6-meter width and height.

Batteries

The batteries on *Perseverance* have a total storage capacity of around 200 kWh. Such a battery weighs about 1500 kg and has a size of about 1.1 m^3.

A 400 and 600 kWh battery have been tested using the calculations from chapter 8. With some design alterations, a 400 kWh battery can be added. However, this will come at the cost of living space and increasing the yacht's weight. The weight and size of this battery increase linearly with the energy storage size. So, the 600 kWh battery already weighs just over 3 tonnes and is 3.3 m^3. Such a block cannot be fitted to the yacht without significant design changes.

Overall impact

As *Perseverance* is already equipped with a hydro generation system, adding the turbine and generator does not require additional space. This part of the system is included in the propulsion system, and apart from this, only the energy storage part takes up more space. In the next section, several adjustments are suggested to the design. From a realistic viewpoint, this is a challenging process, as any changes would have to be completed during a refit.

9.1.3. Success rate for scenario

The success rate for the current setup on board *Perseverance* is calculated using the energy balance part of the method as outlined in section 8.3 with the rules as set up for the scenario in chapter 4. The resulting success rate is 0.0%, and the generator is on for 232 hours on average, as presented in figure 9.6. The design is adjusted in battery size, sail area, and propeller diameter to test the impact of a more hydro-generation-focused design. Any changes are measured from this base point.

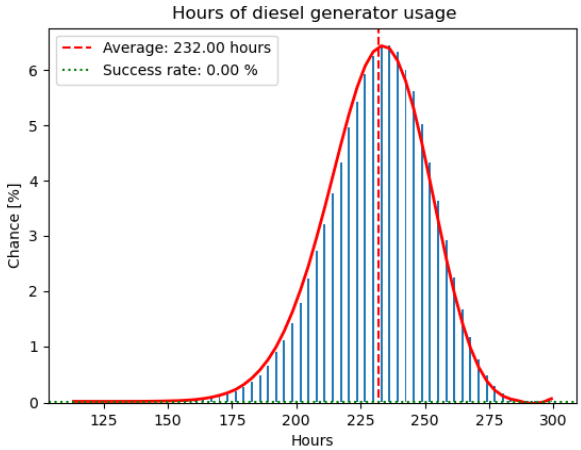


Figure 9.6: Design as built on *Perseverance*

The design has been assessed with the original battery and increasing sizes with increments of 200 kW, figure 9.7. With these increases, the success rate of the scenario remains zero. However, it does result in a shift of the hours of generator usage to the left. Starting at the red 200 kWh curve, with an average of 232 hours, it decreases by 28% to 166 hours for the green 800 kWh battery curve. Increasing the battery size from 200 to 400 kWh reduced it only by 9% to 211.

Unreasonable battery sizes are required to achieve a high success rate using only the batteries as a variable. For an 80% success rate, about 2500 kWh of battery storage is needed. Such a battery weighs approximately 19 tonnes and has a size of 14 m^3. For 99%, the battery increases even further to 2870 kWh. These batteries would account for over 20% light ship weight and more than 15% canoe body volume. Such adjustments to reach a higher success rate for the scenario are unrealistic.

Increasing the propeller size by 10% slows the boat down with increased resistance. Still, the overall average output increases from 19.25 kW to 20.8 kW. This results in a 4% decrease in generator use to 222 hours. A 20% increase results in a similar change. This means that the larger propeller does reach a limit, considering the balance of a larger output versus the increased resistance. It is not beneficial to keep expanding the propeller size, and an optimum is to be found.

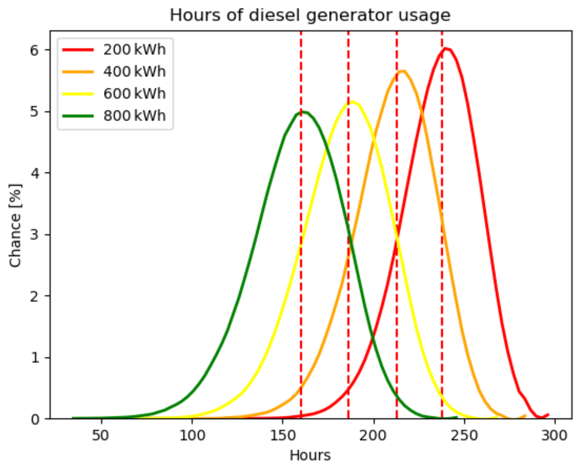


Figure 9.7: Increasing battery size for *Perseverance*

Increasing the sail area makes the boat sail faster in general. However, revising the sail area is always combined with other adjustments to acquire a new balance, such as adding ballast weight or changing its location. 5% more sail area results in a 3% decrease in generator use to 224 hours. By increasing the sail size even further, similar results are achieved. The main change is an increased free sailing area. Although this benefits overall fuel savings, it is not beneficial for the scenario, as sailing in this state will only cost energy. It is better to sail fast rather than often. And like the propeller, it is not beneficial to keep increasing the sail size as the negatives will start to outweigh the positives.

Two final alterations were also studied: a switch in the generation quadrant and a decrease in hotel load. The change from Q1 to Q3 increases the average charging rate using hydro generation by 23%, from 19.25 kW to 23.68 kW. This reduces the generator hours by 5% to 221 hours. A 30% decrease in hotel load has the same effect as doubling the battery size and decreases the generator hours by 9%.

A combination of adjustments was tested to impact the success rate. All changes are deemed within the realm of possibilities and can be changed without changing more variables. A revision of the sail area is not selected due to the low impact and need for more variable alterations. The chosen changes are a 10% more propeller diameter, a 30% less hotel load, and a doubled battery size. These changes are the most impacting of the considered changes for the scenario.

The combined effect is a decrease in generator usage of 41%, as plotted in figure 9.8. There is also a very slight change, of 0.02%, that the scenario is a success. The 41% decrease is nearly two times larger than the sum of the separate solutions combined at 22%. The effect of one change can influence the other changes and act as a multiplier. The nature of this multiplier and how it affects the outcome of the success rate requires further research.

Changing generation to the third quadrant causes the output to increase to 27.95 kWh on average. This decreases generator usage by another 9% and increases the success rate to 0.42%. This is quite a radical design change and influences the propulsion system significantly. Therefore, it is not considered in the remainder of this section.

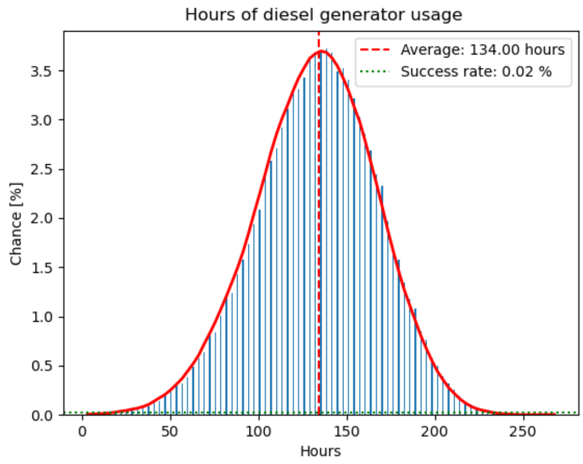


Figure 9.8: The generator hours for the combined adjustments

9.1.4. Impact on fuel consumption and emissions

The 41% decreasing generator usage does not result in a similar decrease in emissions for the entire trip. For this, the running time of the generators or main engine for propulsion would also have to be considered. To get a better idea of this number, the running time from the main engine would also have to be considered. The 95-hour decrease in generator run time does save over 750 liters of fuel if an 8 liter/hour fuel consumption is assumed. Considering that 3.26 kg of CO_2 is emitted per liter of diesel, the emission savings are also crucial.

9.1.5. Impact of sailing regions and yacht usage

To increase the understanding of the impact of the sailing region, the output plot from the PPP, figure 9.4, is considered again. As mentioned before, the highest output is achieved sailing with 90 degrees true wind with a wind speed of 12 to 16 m/s. So, if there is wind data that also has a high occurrence of this wind, the output will increase. The optimal sail area only has wind of about 14 m/s coming from 90 degrees.

Crossing from Gibraltar to the West Indies is a reasonably favorable route as it is often downwind, and the wind peak mostly coincides with the area suitable for generation. If the same crossing is sailed back, and the wind is often in the lower true wind angels, more of the trip would have to be motored. This does not affect the success rate of the scenario, and the balance between generation and free sailing stays relatively even. The overall diesel generator usage is 9% less than the baseline. But the distribution of the events is more in favor of motoring than sailing. So, overall emissions increase for the way back as the propulsion engine is used more often.

If the hotel load is decreased by 30%, the generator hours decrease by 9%. This also means that if the energy on board the yacht is used more efficiently, the success rate for the scenario increases. Currently, the overall energy balance on board *Perseverance* is negative as more energy leaves the system that is generated, on average. A successful crossing occurs exclusively in perfect sailing conditions. A higher input is reached when a yacht sails more and hydro-generates earlier. Together with a decreased hotel load, a positive balance is achieved. However, this is only possible if the sailing yacht is desired to be used likewise.

9.1.6. Conclusion

The performed calculations on *Perseverance* show that the yacht is not designed to cross the ocean without a diesel generator. Hydro generation is more of an added-on feature than a fundamental energy supplier. Still, with some adjustments to the system, a minor but noticeable boost in the success rate for the scenario is achieved. The changes will not enable the yacht to cross the ocean without using fossil fuel for its hotel load. However, the changes will significantly decrease the hours of diesel generators running to supply the hotel load. By changing three significant but achievable factors, the hours of diesel generator usage are reduced by 41%.

The 41% decrease is not the highest effect that can be achieved. By optimizing the balance between all the options, an optimum could theoretically be reached. However, these changes will influence other parameters and impact the yacht's overall design.

9.2. Yacht 2: Concept

The second yacht used for analyzing the scenario is the design for *Project Zero*. This Panamax ketch is selected for two reasons. Firstly, it is on the larger side of the usable spectrum of the method. Secondly, all the dimensions needed are already available for use. This way, it is tested for usability during the design phase. *Zero* has two differently sized propellers. For this method, an average is taken. All displayed data is these two propellers combined. The pod-mounted propellers allow for generation in the third quadrant.

Zero is designed with an above-average focus on hydro generation compared to other sailing yachts. This resulted in two relatively large propellers and an abundance of energy storage. First, the design data is used to look into the success rate of the scenario. Once completed, this data was varied to look into the limits of hydro generation. Compared to the previous example, these limits are sought the other way around, as *Zero* is by design more than capable of reaching a high success rate. The limit is determined as the turning point when a perfect success rate is no longer achieved due to the decrease in hydro generation capabilities. With the average trip speed of 12.26 knots for *Zero*, the trip duration for the 3200 nautical miles is estimated at 260 hours. The hotel load used under sail is 26.21 kWh on average. It is considered a constant average load.

9.2.1. Prognosis of output

The energy generation prognosis performed in the method's basis consists of two parts: a determination of the propeller operating points using the propeller characteristics and an estimate of the produced energy by the propeller. An explanation of the executed calculations is provided in section 5.1.

Propeller operating points

Zero will generate in the third quadrant with the B4-70 selected for both propellers. Following the method in section 5.1.1, three pitch settings selected:

1. Max C_p - $C_p = 35.49$ % and $\eta = 45.04$ %
2. Middle - $C_p = 25.76$ % and $\eta = 61.66$ %
3. Max η - $C_p = 16.08$ % and $\eta = 72.71$ %

The three points are visualized in figure 9.9. All three operating points are found on different $\frac{P}{D}$ curves. The maximum efficiency has a $\frac{P}{D}$ value of 1.4, the middle point has a $\frac{P}{D}$ value of 1, and the C_p point is located on the curve $\frac{P}{D}$ = 0.6.

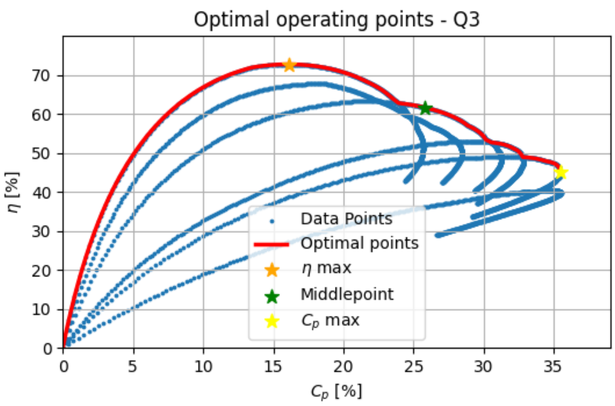


Figure 9.9: Available operating points in Q1 for the B4-70

Produced energy

The maximum output is plotted for each point in figure 9.10 using the calculations presented in section 5.1. This also shows the speed at which the yacht should have sailed to reach the output. The difference between these lines is the speed loss. This loss in speed is also plotted on the right y-axis as a percentile loss. The loss is lower for higher efficiencies. But the output decreases as well. A balance is sought within the process to minimize speed loss and maximize energy output. For some speeds, switching to a higher efficiency setting becomes beneficial. The speed loss decreases, and the relative output increases. For *Zero*, this occurs at speeds below 16 knots. The large propellers cause a high delta in speed loss between free sailing and generating. The high output allows for an earlier switch to higher efficiency settings.

Figure 9.11 shows this balance. The points on the x-axis are the free sailing speeds, the speed at which the yacht would sail without generation. If the generator is turned on, it will first be set to the max η point, the first point on each line starting at the free sailing speed. Next, the middle point is reached, and each line ends at the max C_p point on the left side of each line. For free sailing speeds below 16 knots, the change in output is insignificant for the final two points. From 12 knots on, the difference between all three points is negligible. However, the speed loss is significant. At these speeds, it is beneficial to set the propeller to a higher efficiency and sail faster. With the relatively large propellers on board *Zero*, this effect is noticed sooner than on other yachts.

The desire for hydro generation is unlikely at lower speeds as the loss of sailing speed can reach 10% or more. Two limits were introduced to prevent this. Firstly, a lower limit for hydro generation at 120% transit speed. Secondly, a lower limit for free sailing at 80%. For *Perseverance*, these limits are set using the waterline length, as previously mentioned in section 2.1.2.

- 80% of transit:
  fn = 0.21 [-] and v = 9.27 [kts]
- 100% of transit:
  fn = 0.27 [-] and v = 11.59 [kts]
- 120% of transit:
  fn = 0.32 [-] and v = 13.90 [kts]

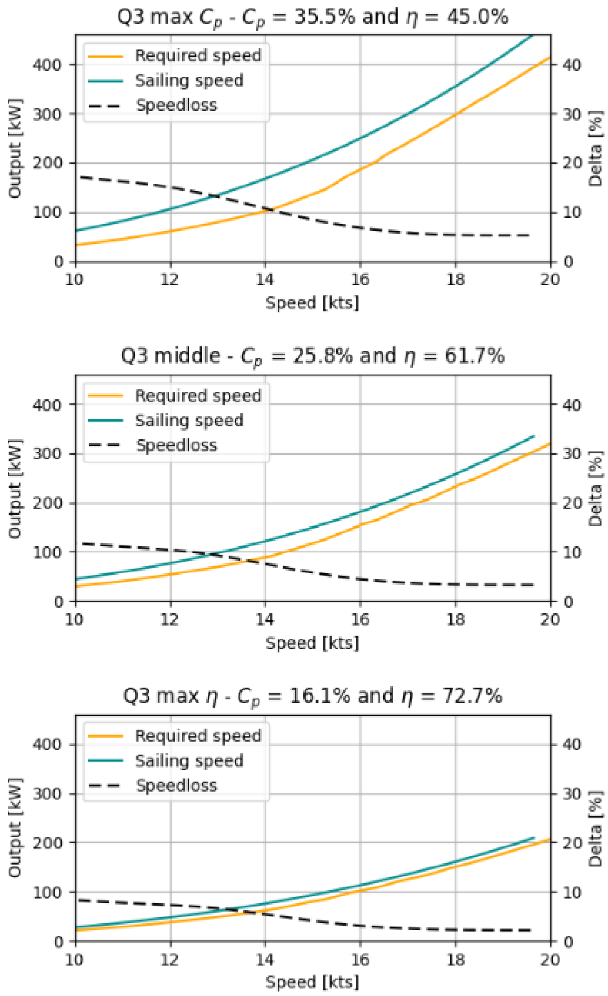


Figure 9.10: Maximum energy output for three settings

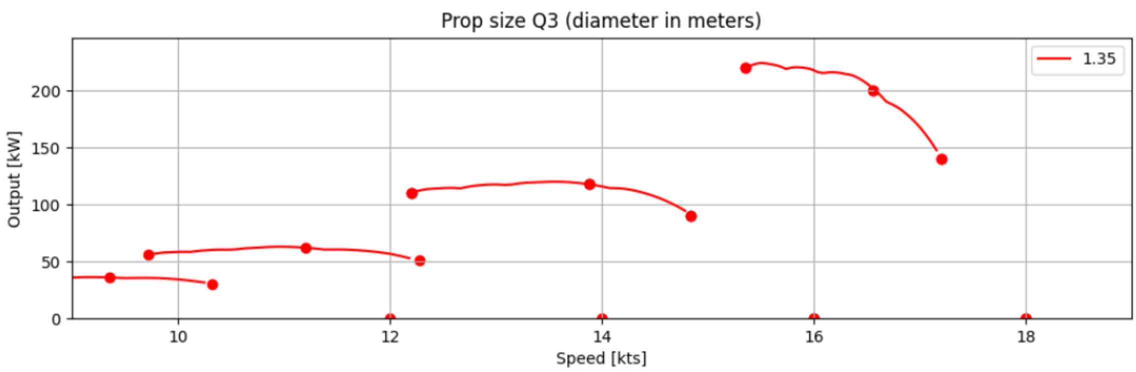


Figure 9.11: Balance propeller settings *Perseverance* for both propellers combined

There is not any available data for *Zero* as the yacht has not been built yet. However, the hydro generation system on board the yacht is designed around a specific point of 250 kW energy output at 16 knots sailing speed (Leslie-Miller & van Someren, 2022). This point is reached in the first plot of figure 9.10.

A prediction is made using a PPP of the possible output and combined speed for all wind speeds and directions. This gives a better idea of the balance between output gain and speed loss. This PPP also adds the possibility of combining the output data with wind data to determine the success rate for the scenario. The results of this PPP are displayed in figure 9.12, including the free sailing area and motor(sailing) boundary. The yacht's increased size makes it harder to reach the sailing threshold, as more wind is required. While the free sailing area is relatively increased, the zone for generation is decreased compared to the previously analyzed yacht. With the larger propellers, it becomes harder to overcome the generation threshold, and the vessel will remain longer in the free sailing zone.

The highest output is achieved sailing with 90 degrees true wind with a wind speed of 12 to 16 m/s. So, if there is wind data that also has a high occurrence of this wind, the output will increase. The average energy output when hydro generating, for the wind data in the scenario, is 76.6 kW

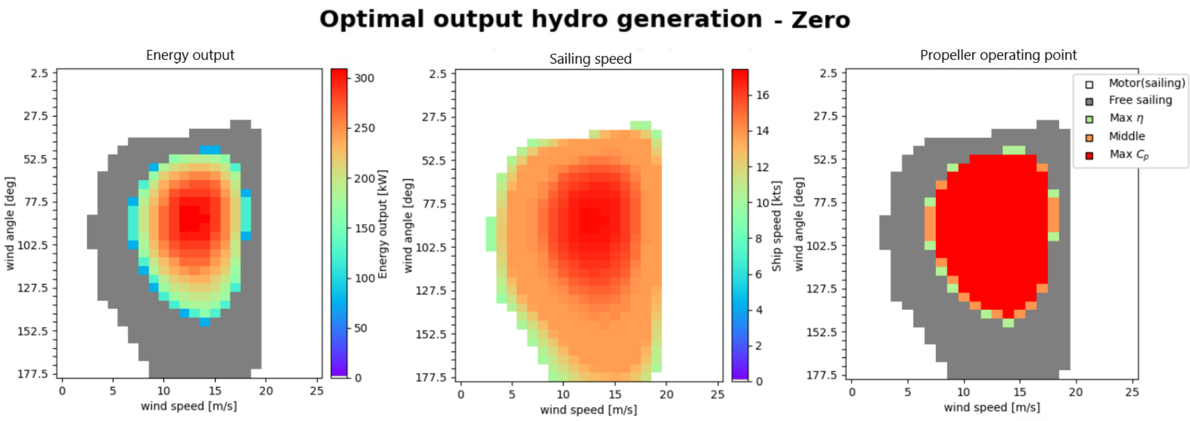


Figure 9.12: Output and speed for *Zero* as built

9.2.2. Physical impact on the system

The physical impact of hydro generation on a yacht's design is derived from each of the three parts of the system. The propeller is the turbine, the generator is the converter, and the batteries are the storage system. With *Zero*, the sizes of these parts are already known. The calculations are checked using these known sizes. Additionally, a variation is completed to determine the impact on the success rate of the scenario and the limits. A backward approach is used to determine *Zero's* limits, as it is designed with hydro generation in mind. So, the systems were decreased in size to see at which point the success rate became too small.

Propeller

For *Zero*, the average propeller diameter is 1.35 meters. This is an input value for the method and does not need to be checked. The propeller is a controllable pitch propeller designed from a propulsion perspective and is used for generation in the third quadrant. For this scenario, a B4-70 propeller is selected.

As described in chapter 6, a variation study is completed using the method. The goal is to determine the effect of a 10 and 20 percent decrease. Any smaller is deemed unrealistic without significant design changes. It is plotted in figure 9.13, detailing the smaller output and the decreased speed loss.

Generator

The generator on board *Zero* is the same electric machine used for propulsion. Therefore, the estimated size does not correspond with the method's estimation as performed in chapter 7. The method approximates a generator with a 2.35-meter length and 1.0-meter width and height. However, this is for the input of both props combined, and by design, this input is split. The generators are then approximated at 1.87-meter length and 0.83-meter width and height.

Batteries

The batteries on *Zero* have a total storage capacity of around 5000 kWh. Such a battery weighs over 35000 kg and has a size of about 27.5 m^3. This is a large battery for a yacht of this size, which accounts for 15% of the light ship weight. On comparable vessels, such a battery would not be required. However, more energy storage is needed for its designed zero-fuel purpose.

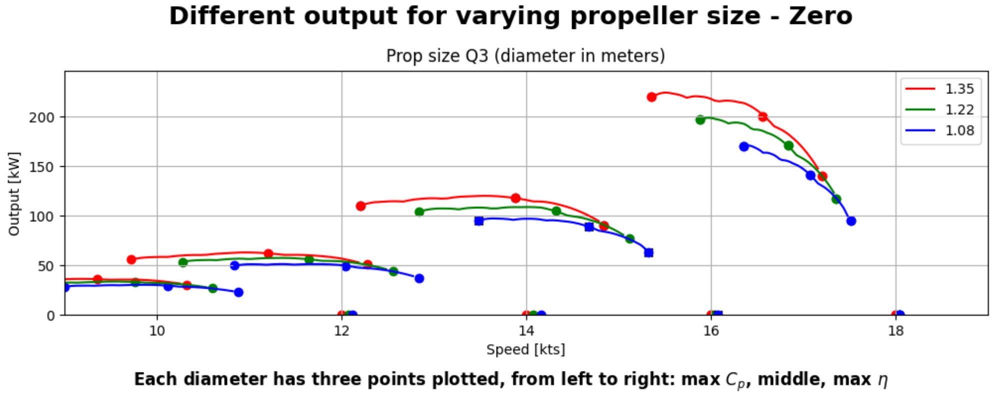


Figure 9.13: Propeller variation for *Perseverance*

Overall impact
As *Zero* is completed with an extensive hydro generation system. The system is included in the propulsion system. Based on the scenario, the size of the system could be decreased to increase free interior space. However, the goal of *Zero* surpasses the scenario's goal significantly as it is to become fossil fuel free. This makes a decrease in the hydro generation systems' capabilities an unrealistic suggestion.

9.2.3. Success rate scenario

The success rate for the designed setup on board *Zero* is calculated using the energy balance part of the method as outlined in section 8.3 with the rules as set up for the scenario in chapter 4. The success rate with the designed setup on board *Zero* is 100%. Unlike *Perseverance*, *Zero* is designed with the purpose of sailing without fossil fuels. The design is adjusted in battery size, sail area, and propeller diameter to test the impact of a less hydro-generation-focused design. All changes are made to search for a success rate of 99%. This is deemed to be the limit.

For the scenario, the change to a smaller battery was tested. The space savings were determined for those smaller batteries with the addition of a generator on board. The limit where the success rate decreases below 99% is determined using the method at 3450 kWh. The battery decreases in size by 30% to 19 m^3 and in weight by 26% to nearly 26000 kg. From this point on, a decreasing battery size is provided in table 9.1. With this decrease, the number of generator hours increases as presented in figure 9.14. A decision, based on the yacht usage and preference, is made on how much battery size decrease would be preferable. For the scenario, a 31% decreased battery size would be possible, indicating the limit.

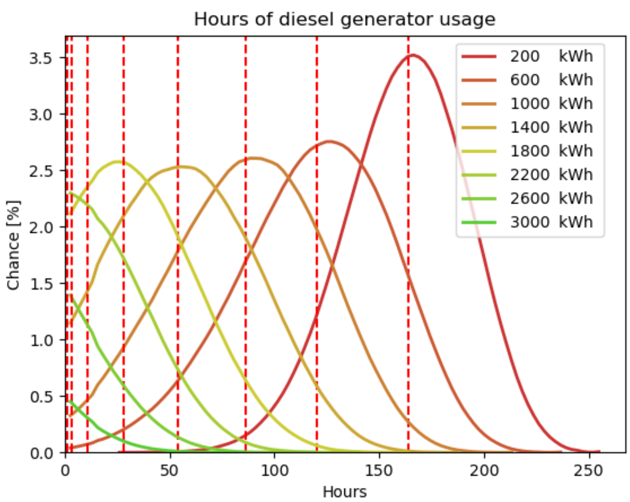


Figure 9.14: Generator usage on *Zero* if the battery size was decreased

For the following adjustments, a battery of 3450 kWh is used as the effects are otherwise unnoticeable. Smaller propeller dimensions were tested. It is concluded that a 10% or 20% propeller decrease does not affect the success rate. The first change is noticed from 30% less diameter. For the sail area, the limit occurs at a 10% size decrease. A similar effect to the multiplier for combined increases occurs if the limit is sought the other way around. By combining a 10% propeller diameter, 10% sail area, and 30% battery decrease, a success rate of 99% is still achieved.

Table 9.1: Success Rates for Various Energy Consumption Levels

Success Rate (%)	Energy Consumption (kWh)	Volume (m³)	Weight (kg)
0.0	200	1.1	1504.0
0.14	600	3.3	4511.0
2.05	1000	5.49	7519.0
10.81	1400	7.69	10526.0
31.65	1800	9.89	13534.0
61.14	2200	12.09	16541.0
85.5	2600	14.29	19549.0
96.75	3000	16.48	22556.0

9.2.4. Impact on fuel consumption and emissions

By changing the system to the limit and achieving a 99% success rate, no additional fuel should have to be consumed. Theoretically, the emissions produced during the production of the larger batteries could be limited this way. However, *Zero* is not only designed for the exact purpose as proposed in the scenario. So, such a change cannot simply be suggested based on this information.

9.2.5. Impact of sailing regions and yacht usage

As *Zero* is over-dimensioned for the scenario, other sailing regions with reasonably favorable wind profiles do not influence the overall success rate. The hotel load could also be increased during a crossing, such as the one in the scenario.

9.2.6. Conclusion

Zero is over-dimensioned to achieve the scenario. The limit to reach the scenario is sought by decreasing all systems in size. If the yacht were designed for just the scenario, a combination of systems could be shrunk in size. Finding a limit is easier if the yacht already successfully reaches the limit, as decreases in, for instance, battery size can more easily be done without the needed evaluation if the changes fit the design limits.

9.3. Comparison

The method works well for searching the limits that determine the success rate. It accurately shows the impact of a varying battery or propeller size, including the change in the generation quadrant. However, it does not provide a clear insight into the changing sail area, which requires changing multiple inputs. The method is used in two ways to search for the limit at which hydro generation becomes a feasible solution to cross the ocean without using the generator. By searching with an improving system capability for yachts that cannot achieve the scenario or vice versa by searching with a decreasing system capability.

Other scenarios could also be introduced if the correct trip data is available. With the method considered operational, the third sub-question is answered: *How can a selection method be formed to determine which hydro generation configuration would suit a specific sailing yacht best?* The designed method, which consists of an output prognosis, a determination of the physical impact, a fuel savings estimate, and a usage influence estimate, can aid in selecting the hydro generation configuration and dimensions. Its calculations are based on the inputs for a specific yacht.

Several conclusions are drawn from comparing the two yachts used for the scenario. Firstly, a larger vessel helps when it comes to hydro generation. It provides more freedom for larger battery sizes and uses relatively less energy for its hotel load. In general, larger yachts sail faster, and speed is the most predominant variable for generation output. Secondly, the impact between the first and third quadrants is design-specific. Throughout the test with the method, the gained energy output by switching to the third quadrant varied between 5% and 30%. The comparison between the two quadrants becomes biased, as the design method automatically switches to the highest output. Therefore, it cannot be used to determine if a more average gain is made by shifting between quadrants. Thirdly, the effect arising from one change can benefit others and act as a multiplier. Not focusing on one change but rather on multiple smaller ones increases the overall benefit. This way, there is an optimum to be found.

The best idea is to not sail in a straight line. Instead, one should navigate to more favorable wind regions. Routing software is needed for the method to consider this in the calculation. As the selected route is mostly downwind, adding an appropriate sail set for these conditions would also increase the chances.

From the scenario, an answer can also be formed for sub-question four: *To what extent does the implementation of hydro generation influence sailing yacht design, and which choices indicate the implementation limit?* The difficulty of adding a hydro generation system depends on the moment of implementation and the design of the yacht. The application is relatively straightforward when a hybrid propulsion system is the basis on which hydro generation is added. Only the additional energy storage could pose a problem. However, when a system is added to a traditional propulsion setup, the batteries still require the most space. In general, it is concluded that energy storage causes the prevailing problem. A definitive size depends on the requested range for sailing without running a generator.

There are two limits to be reached concerning hydro generation. Either the yacht's design cannot accommodate a more extensive system, making it impossible to achieve the desired success rate for a predefined scenario. Or when achieving a 100% success rate, decreasing the size of the components until this perfect 100% is not possible anymore. Whether the first or second limit is reached depends on the original design of the yacht.

10 Conclusion

For this thesis, a novel design method was constructed to assess the influences of hydro generation on sailing yacht designs during an early design stage. The main research question that is answered with this research is:

How can the most effective hydro generation implementation be selected per individual sailing super yacht, based on the early stage yacht design requirements?

To answer this question, four sub-questions were formulated. These have been answered throughout the various chapters of this thesis. Each sub-question is reviewed in this conclusion, after which an answer to the main research question is provided.

The desired moment to use the method is during the early design stages. However, all calculations performed in the design method require input variables. So, they can only be performed during the early design stage if the variables are already known. To determine a list of these available variables, sub-question one is introduced: *What early-stage design elements are significant on board a sailing super yacht, and which of these variables influence the hydro generation system?* The dominant design elements are general arrangement, appendage design, propulsion system, loading conditions, tank plan, and weight. This is summarized into dimensions and weight as the first and second main drivers in the design method. Not only the main design elements are essential to consider. Additional considerations were studied and used for the design method. The most important considerations are the operational profile and the energy demand, which influence the design elements. These elements influence the overall design. This makes the energy balance the third main driver for the design method. The list was compiled through literature research and the design process at Dykstra Naval Architects. Design considerations such as noise and TRL are more ship or project-specific and not included in the design method.

For a better idea of the current status of hydro generation on board yachts, the following sub-question was compiled: *What solutions for hydro generation are currently applied on sailing yachts, and what solutions can be applied in the future?* With all recent developments, it is hard to pinpoint what has not been done yet. The existing hydro generation solutions are mainly installed onto the propulsion system. There are options on the market for separate systems, but these are standard consumer systems implemented on smaller pleasure craft. Large custom solutions are divided into multiple categories. These categories are combined choices on integrated or separate, shaft line or thruster, FFP or CPP, and fixed or retractable solutions. The idea of hydro generation on sailing yachts is gaining traction, and so are the developments in the hydro generation field. With the added efficiency in the third quadrant, most advancements are found in products that allow this type of generation. The efficiencies for conversion and generation are already relatively high, so the developments in this area are less significant. Still, energy storage systems are expected to keep developing in the coming years with new battery technologies or alternatives such as fuel cells.

A novel design method was constructed in *Python*. It performs several calculations on hydro generator energy output, component dimensions, and operational influences. The method's results are utilized when assessing a yacht's performance during the scenario. The scenario presented in this thesis is an ocean crossing with the hydro-generator as a primary energy producer. It is considered a success if the crossing is completed without using a backup diesel generator. With the method considered complete, the third sub-question is answered: *How can a selection method be formed to determine which hydro generation configuration would suit a specific sailing yacht best?* The designed method, which consists of an output prognosis, a determination of the physical impact, a fuel savings estimate, and an operational influence estimate, can aid in selecting the hydro generation configuration and dimensions. Its calculations are based on the inputs for a specific yacht.

From the scenario, an answer is also formed for sub-question four: *To what extent does the implementation of hydro generation influence sailing yacht design, and which choices indicate the implementation limit?* The difficulties of adding a hydro generation system depend on the existing design and the moment of implementation. Earlier implementation is better as more options remain, hence the reason for creating a design method for application in the early design stage. The application is relatively straightforward when a hybrid propulsion system is the basis on which hydro generation is added. Only the additional energy storage could pose a problem. When a system is added to a traditional propulsion setup, energy storage remains the main problem. However, a converter also needs to be added. In general, it can be concluded that energy storage provides the main problem. A definitive size depends on the requested range for sailing without running a generator.

A limit for hydro generation depends on the set goal for the system. For this thesis, a scenario was introduced to save fuel by limiting diesel generator use during an ocean crossing. A successful transit is one with zero additional fuel use apart from propulsion. Based on the success rate, a limit can be introduced on how often success should be achieved. There were two approaches to reach this limit. Either by increasing the yacht's hydro generation capabilities until the design cannot accommodate a bulkier system, making it impossible to achieve the desired success rate. Or when already achieving a 100% success rate, decreasing the size of the components until this perfect 100% lost. Whether the first or second limit is reached depends on the original design of the yacht. A change in the success rate can be monitored using the method by changing the design parameters, such as the propeller size for the turbine and the batteries as energy storage, from their original value. The effect arising from one change can benefit others and act as a multiplier. Not focusing on one change but rather on multiple smaller ones increases the overall benefit. In this process, there is an optimum to be found. Optimal hydro generation does not have a singular predefined definition, and it can change depending on the design focus, yacht operation, and scenario. With all sub-questions answered, a conclusive answer can be formed for the main research question:

How can the most effective hydro generation implementation be selected per individual sailing super yacht, based on the early stage yacht design requirements?

Adding a hydro generation system to a yacht is limited by the freedom left in a yacht's design. By adding it during the early design stages, more possibilities and flexibility remain. This shows the importance of a design method that can provide insight into the output and usability of hydro generation during the early design stage with reasonable accuracy. The projected energy output and dimensions might not be the final result, but this is acceptable with all other changes that will occur in the later design steps for the yacht.

The effectiveness of a solution depends on how the yacht is used. To increase the effectiveness of hydro generation, it is not necessarily required to sail more, but faster. Faster sailing can occur with more sail, a smaller propeller, or a larger yacht. Speed is the dominant variable for generation output. A balance is sought by varying variables such as sail area, propeller diameter, battery size, and the generation quadrant with the design method. These balanced variables are then linked to the available solutions, as determined in the second sub-question. Each implementation has limitations, and it is impossible to accommodate any system to any yacht. If, for instance, a specific turbine area is desired, but the propeller diameter becomes too large, it cannot be installed. Or, when a desired success ratio for a scenario can only be reached if the battery increases with unreasonable proportions, the goal might have to be adjusted. As with all other parts of a yacht design process, improving one part might cause stagnation in another area. It is a balancing act, and the designed method can help. Applying a combination of the design method and manufacturers' details on specific solutions can answer the question of the most effective hydro generation implementation on board a sailing yacht.

11 Discussion

For this thesis, the goal was to answer the main research question:

How can the most effective hydro generation implementation be selected per individual sailing super yacht, based on the early stage yacht design requirements?

The question is answered using a novel design method. This method is not perfect (yet), and the limitations and recommendations are discussed in this chapter. Two of these limitations are caused by the definition of the scope. These effects are discussed first.

11.1. Scope effects

In the scope of this thesis, two defining decisions were made that influenced the outcome of the calculations. The leading defining choice is to work with fewer variables during the early design stage. This caused the results to be less accurate for the final design. However, it also provided the opportunity to perform the calculations much earlier in the design process. A second, more complete method could be designed around a detailed VPP. This could be used in later stages for the detailed design of the hydro generation system. This would also help with verifying the method as a step between extensive real-life testing and the current design method. Additionally, the design method is designed to work for sailing yachts in the 30 to 60-meter range. When answering a research question concerning any sailing yacht, this causes the answers to show a bias toward this range of vessels.

11.2. Limitations

The method was tested using a scenario on two separate yachts. During this, limitations were observed.

- Currently, hydro generation is turned on when a certain speed is reached. It is unlikely that this is always the case, and the decision to engage hydro generation will likely vary per yacht, captain, and crew.
- The method selects the optimal pitch setting. However, this is defined as the pitch setting that delivers the highest output. In some situations, optimal could, for instance, be defined as a specific required energy production to only supply a certain load.
- Due to the setup of the calculations, based on speed steps instead of a wind and resistance balance. It is impossible to compare the exact resistances as the driving force remains constant.
- Currently, the method is only equipped with one propeller data set. This has the benefit that all comparisons are made with the one propeller and allows for better comparison between yachts. However, this propulsion-focused propeller does not give a complete insight into the possibilities of hydro generation. Nor is it currently possible to compare it to a generation-focused propeller. Another generalization is the limited variation in sail coefficients.

11.3. Recommendations

During the research for this thesis, several assumptions and simplifications were made. These areas require further research to come to a more exact answer.

- The current approach to determining the hotel loads is not ideal. Future research could improve the accuracy of these loads. Either by using more detailed multiplication factors. Or through establishing new equations using a database of sailing yachts within the design range of the method.
- Future research is required on a more detailed and exact calculation for speed loss due to hydro generation. The current method skips the energy output curve between free sailing and the first point of generation. By finding a balance in the resistance, the correct curve to connect these points could be found.
- During the scenario analysis, a multiplier effect for the success rate was observed if multiple changes were made. This effect requires further research before in-depth conclusions on it can be formulated.

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A Hotel load formulas YETI

The formulas for each of the groups as determined by van Eesteren Barros (2022) for YETI are as follows:

$$\text{Estimated power } A = 0.1004 \cdot GT + 11.04 \tag{A.1}$$
$$\text{Estimated power } B = 5.063 \cdot 10^{-5} \cdot GT^2 + 0.1123 \cdot GT - 20.53 \ \ (-stabilizers) \tag{A.2}$$
$$\text{Estimated power } C = 3.372 \cdot interior\ space - 93.65 \tag{A.3}$$
$$\text{Estimated power } D = 0.02308 \cdot interior\ space + 5.653 \tag{A.4}$$
$$\text{Estimated power } E = 0.01762 \cdot interior\ space + 5.701 \tag{A.5}$$
$$\text{Estimated power } F = 4.26 \cdot 10^{-5} \cdot interior\ space^2 + 0.1024 \cdot interior\ space + 64.84 \tag{A.6}$$
$$\text{Estimated power } G = 4.744 \cdot LWL - 118.5 \tag{A.7}$$
$$\text{Estimated power } H = 0.103 \cdot interior\ space + 32.12 \ \ (-amenities) \tag{A.8}$$
$$\text{Estimated power } I = 0.135 \cdot interior\ space + 4.591 \tag{A.9}$$
$$\text{Estimated power } I = 0.135 \cdot interior\ space + 4.591 \tag{A.10}$$
$$\text{Estimated power } L = 0.7244 \cdot LWL - 19.57 \tag{A.11}$$
$$\text{Estimated power } M = -0.001776 \cdot LWL^2 + 0.9067 \cdot LWL - 29.01 \tag{A.12}$$

$$\text{Estimated power of stabilizers} = 1.221 \cdot 10^{-6} \cdot GT2 + 0.01308 \cdot GT + 27.26 \tag{A.13}$$
$$\text{Estimated spa power} = 0.0026 \cdot GT + 8.414 \tag{A.14}$$
$$\text{Estimated pool power} = 8.9 \cdot (pool\ size\ in\ m^3) \tag{A.15}$$
$$\text{Estimated jacuzzi power} = 19.3 \cdot (pool\ size\ in\ m3) \tag{A.16}$$

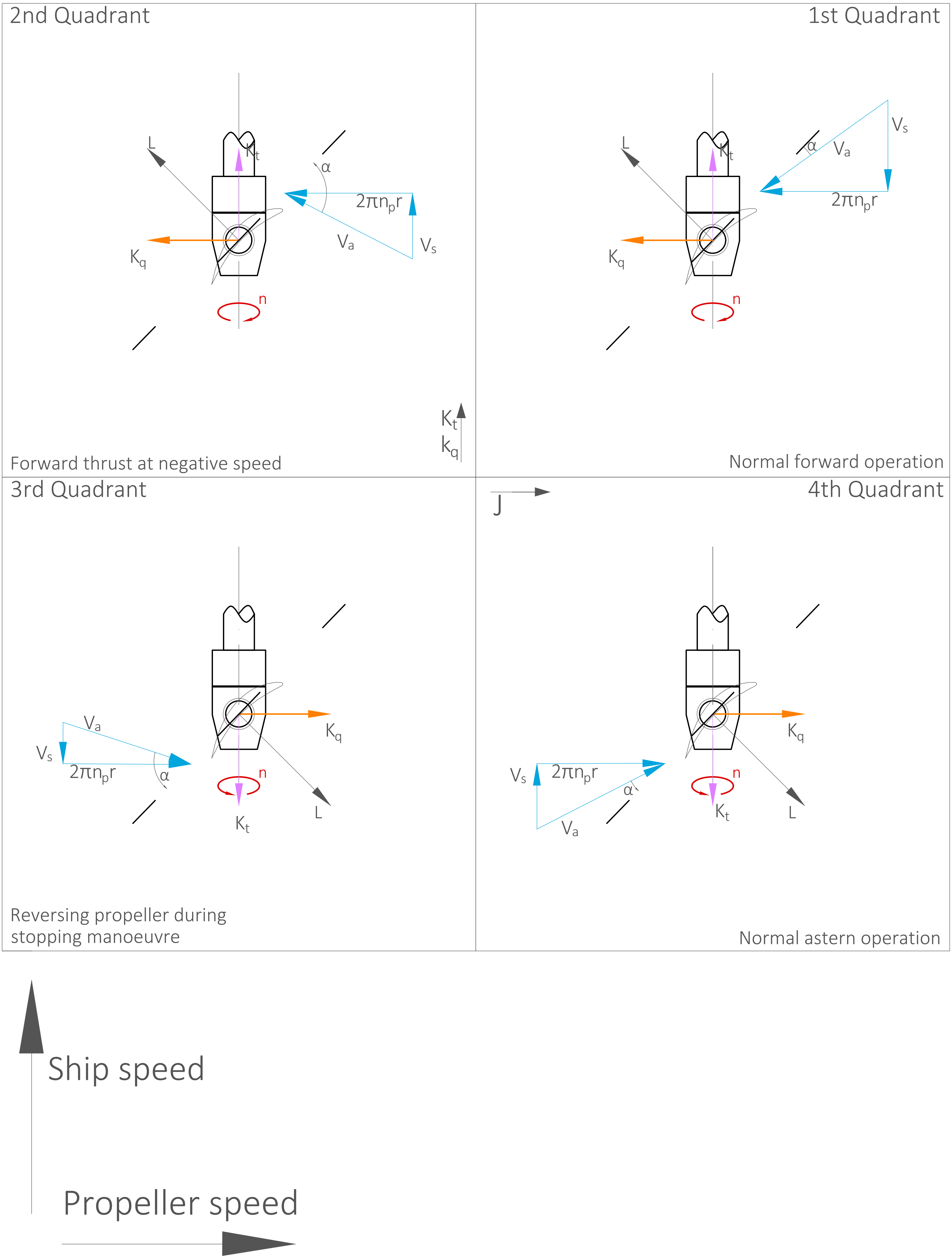
B
Operating conditions propellers

This appendix provides an overview of the operating conditions for propellers, both FPP and CPP, and for propulsion and generation. The appendix consists of four pages each page contains the following content:

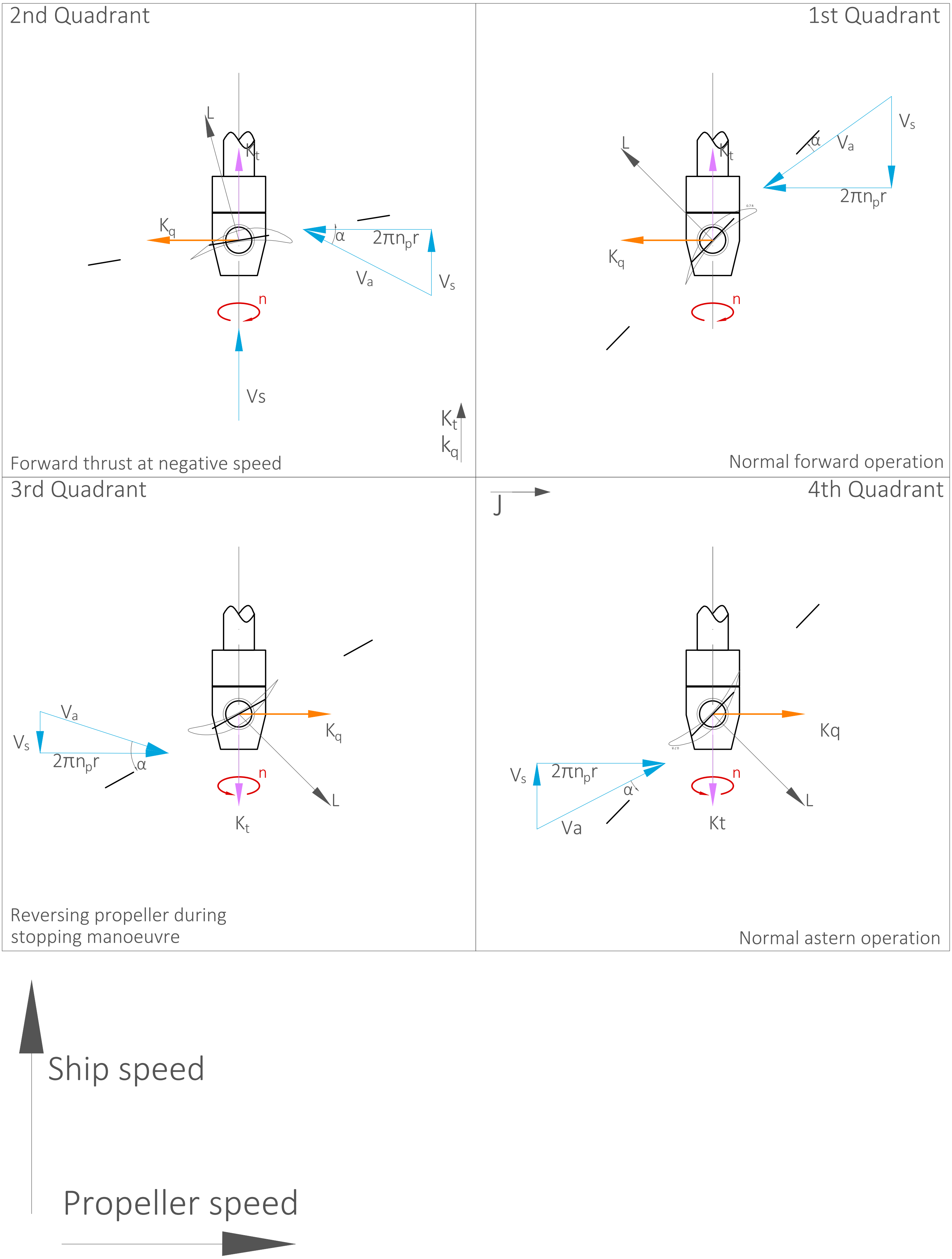
1. FPP propulsion: Four quadrant determination K and J;
2. CPP propulsion: Four quadrant determination K and J;
3. FPP generation: Four quadrant determination β;
4. CPP generation: Four quadrant determination β.

The overviews have been created for this thesis using insights from Klein Woud and Stapersma (2002), Schouten (2016), and internal reports from DNA.

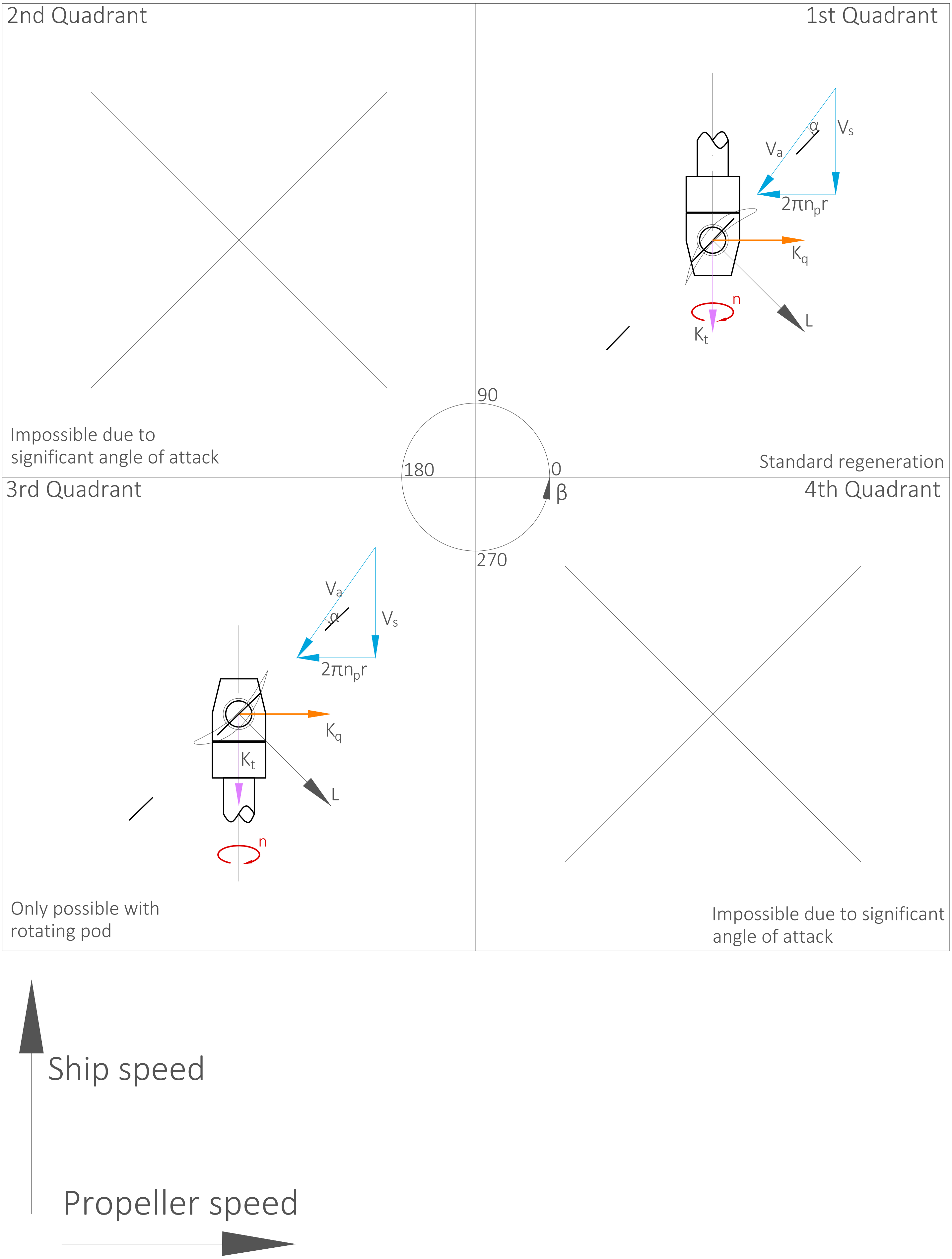
FPP propulsion: Four quadrant determination K and J



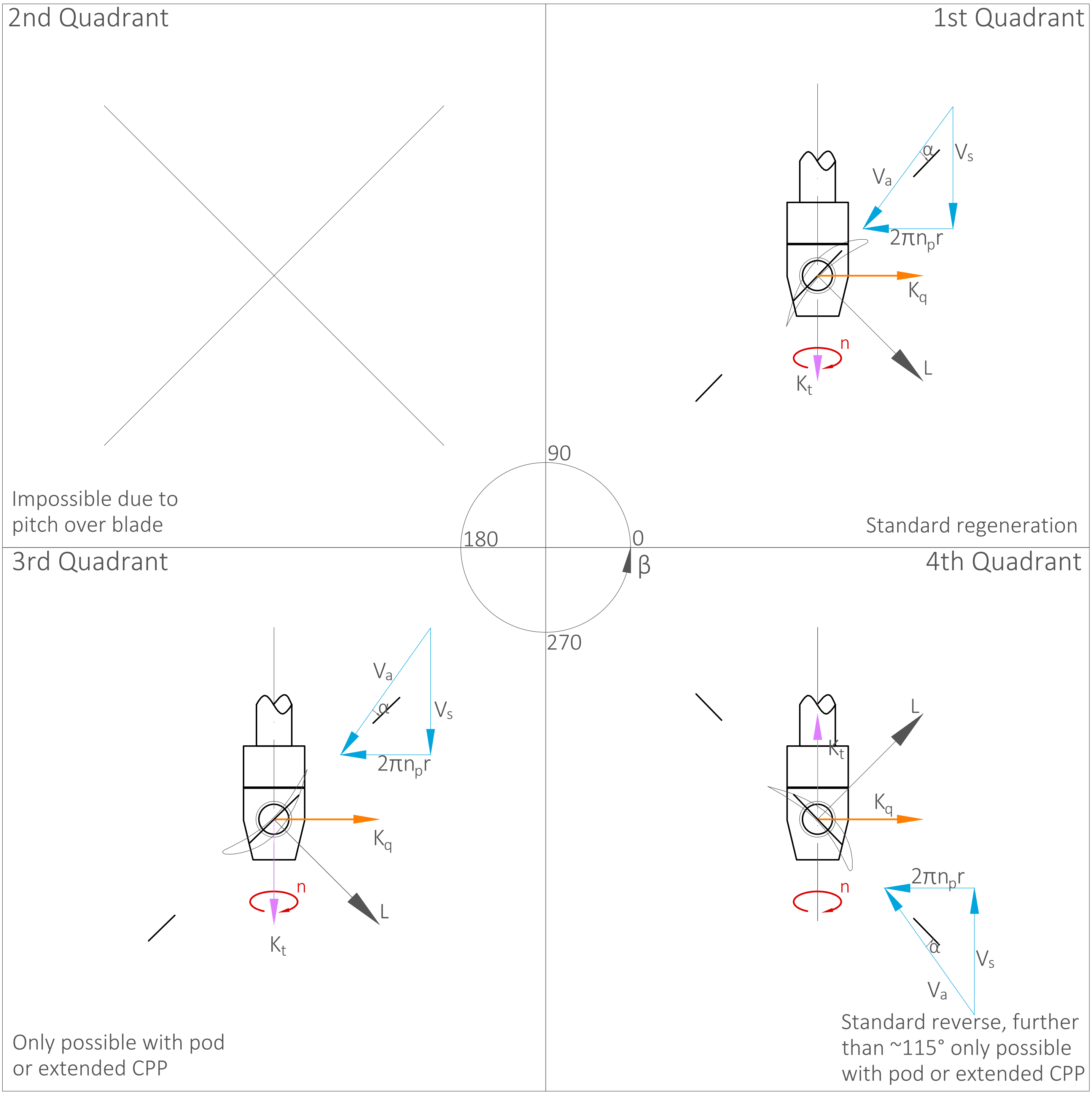
CPP propulsion: Four quadrant determination K and J

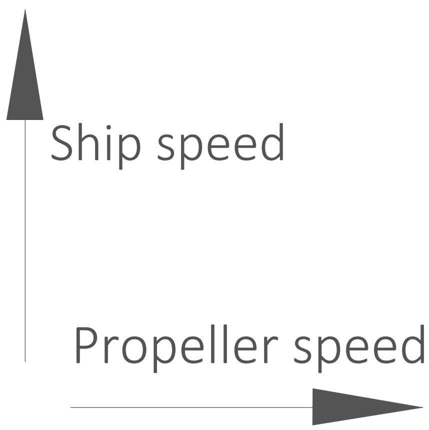


FPP generation: Four quadrant determination β



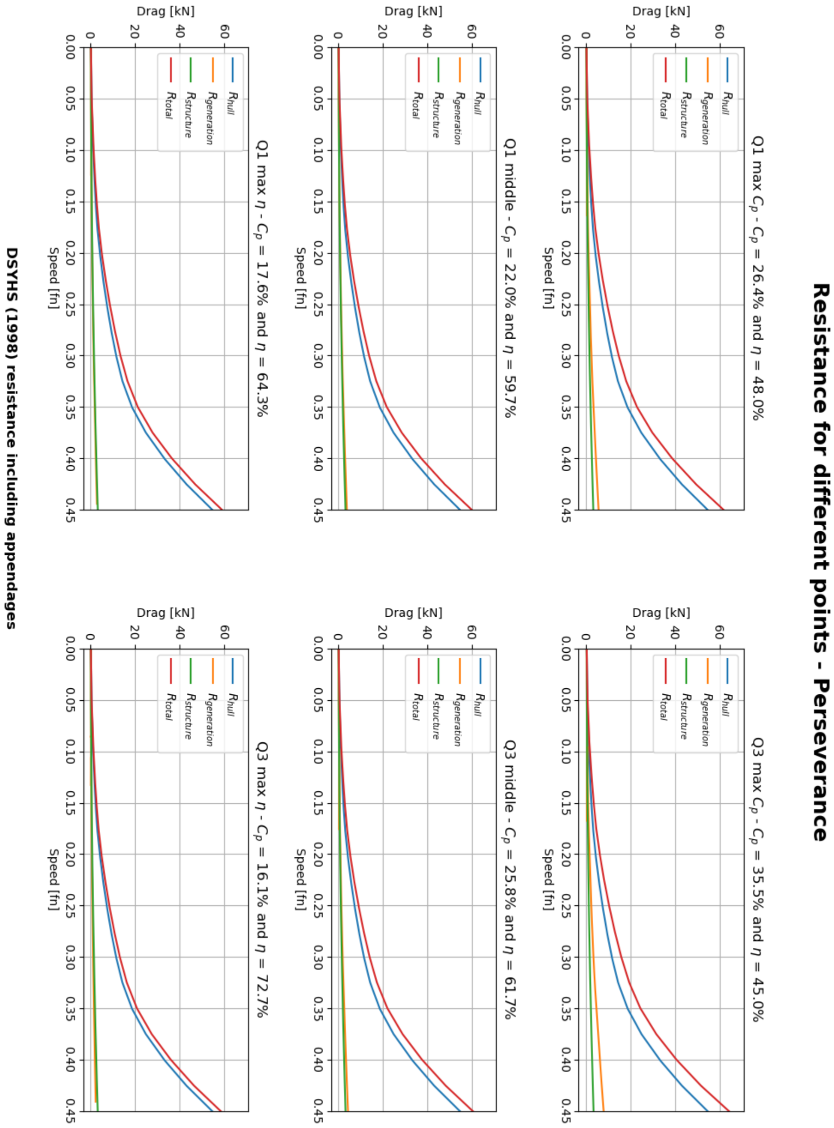
CPP generation: Four quadrant determination β



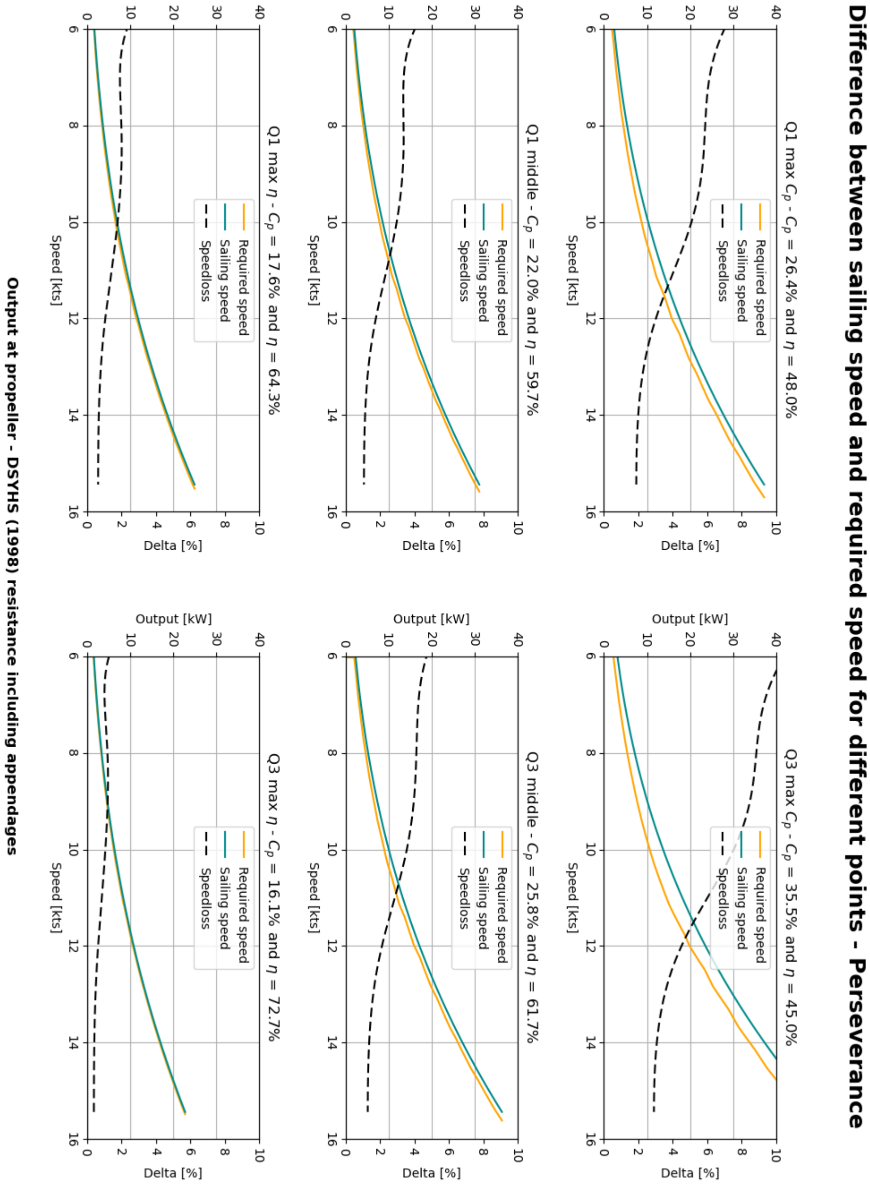


C

Resistance calculations - Perseverance

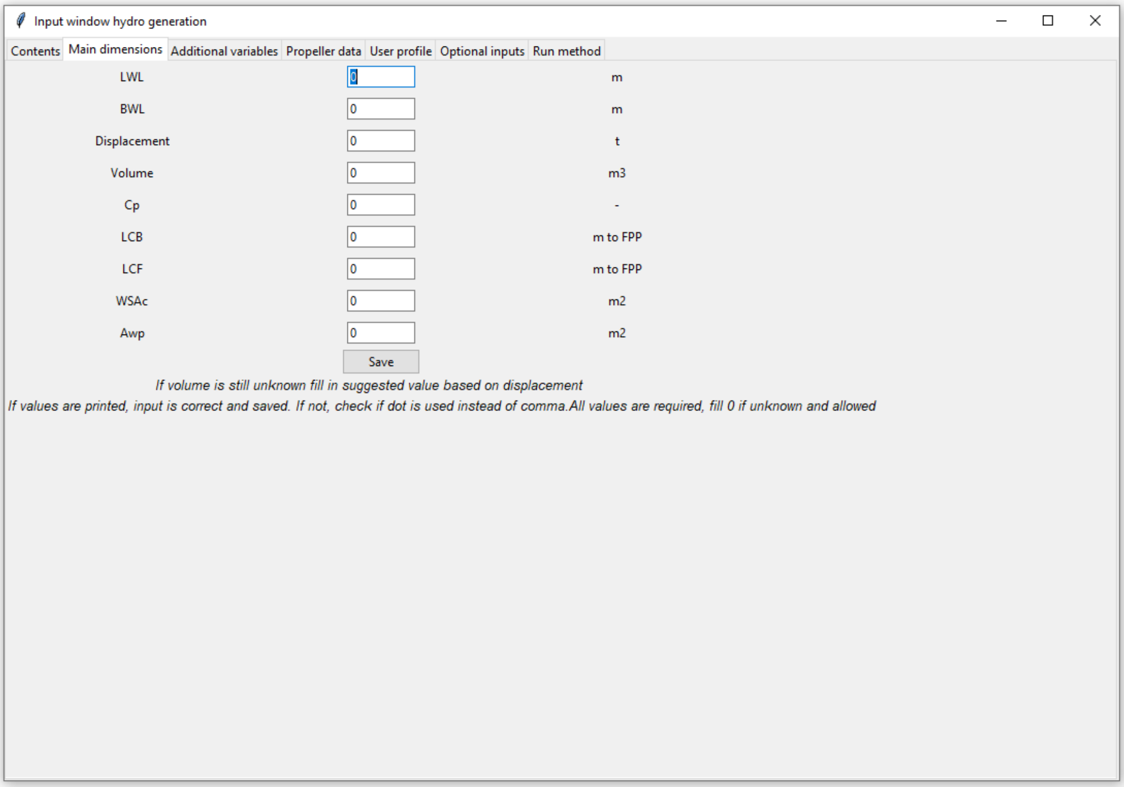


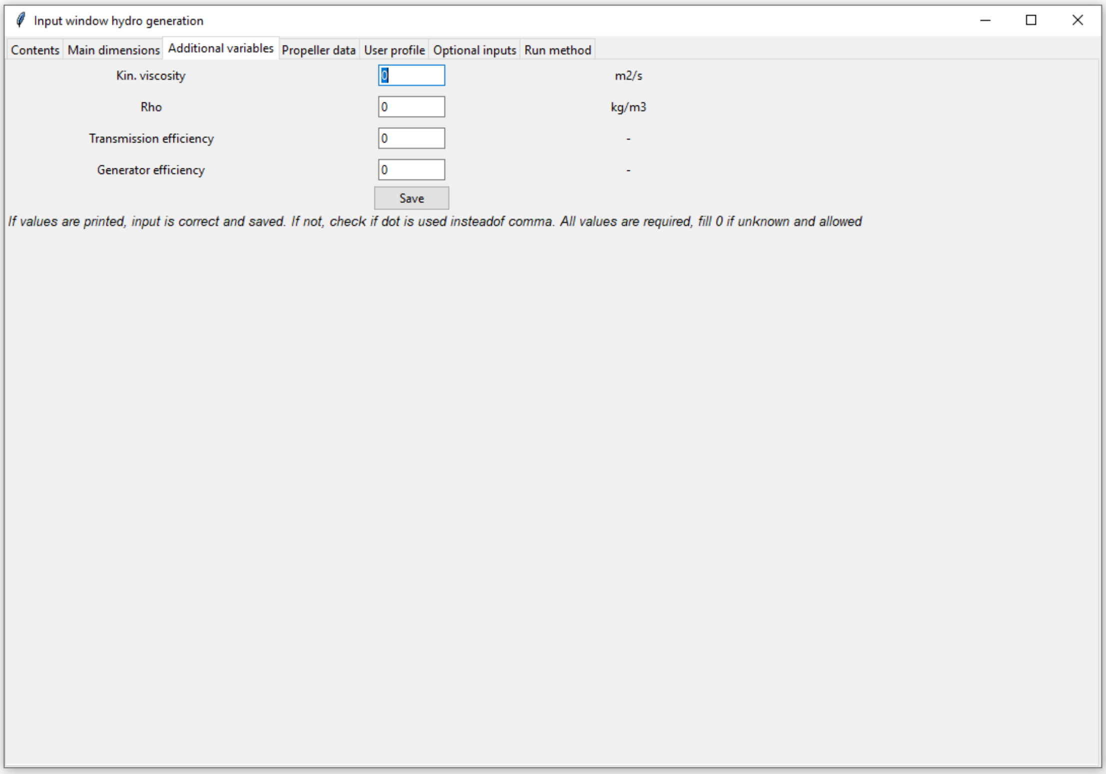
D
Output - Perseverance

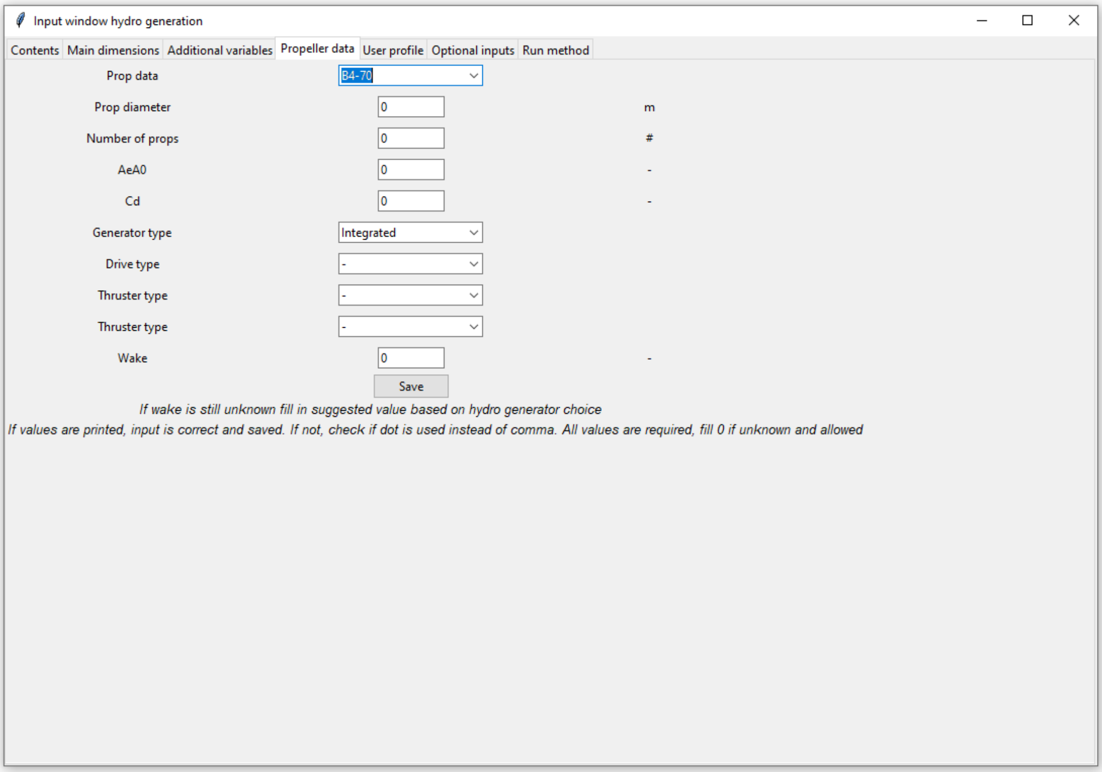


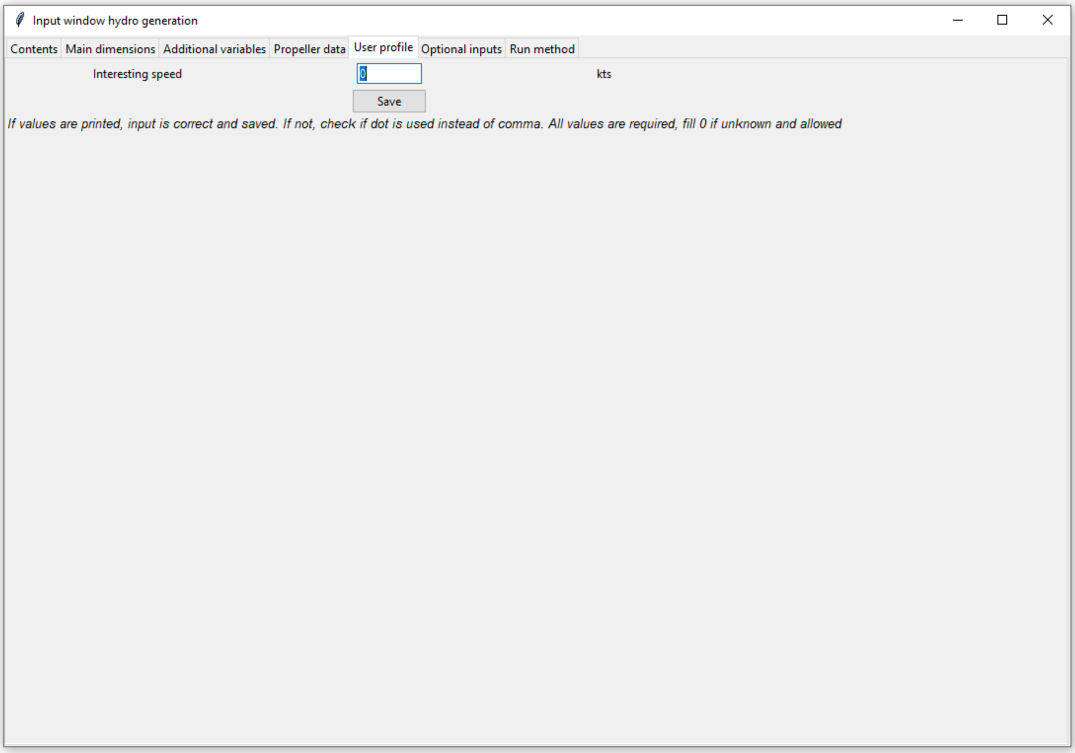
E

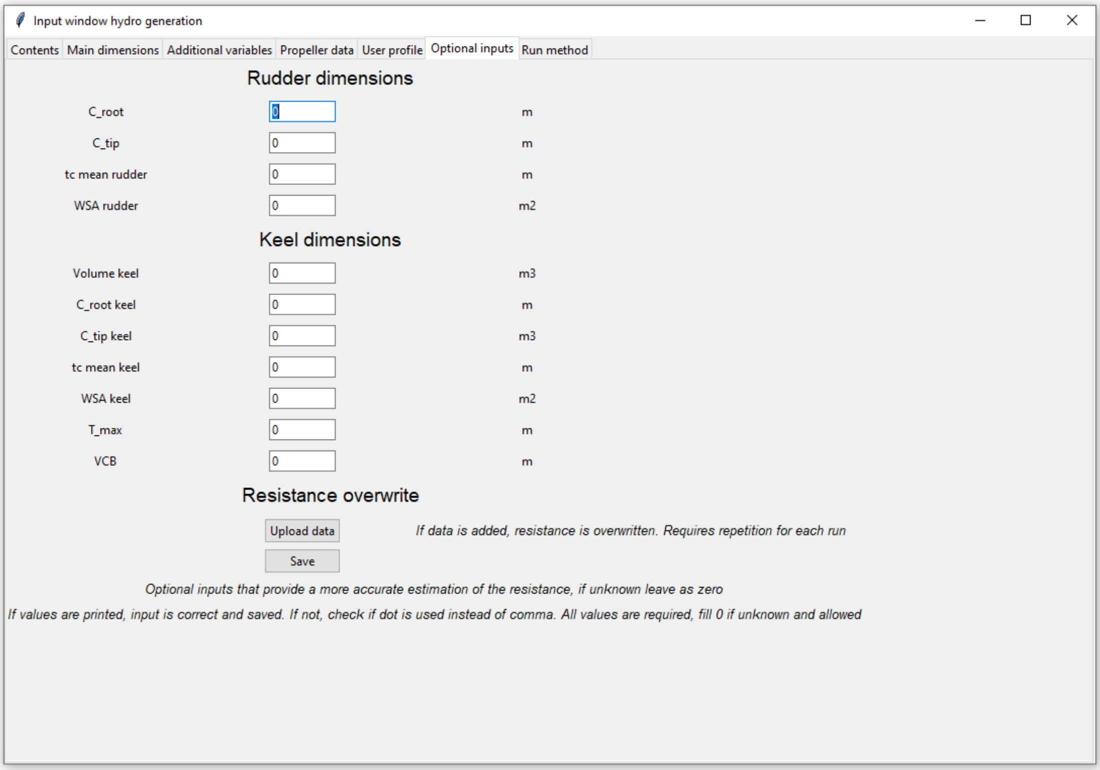
List of input parameters on both yachts




Input window hydro generation
Contents
Main dimensions
Additional variables
Propeller data
User profile
Optional inputs
Run method
Kin. viscosity
0
m2/s
Rho
0
kg/m3
Transmission efficiency
0
-
Generator efficiency
0
-
Save
If values are printed, input is correct and saved. If not, check if dot is used insteadof comma. All values are required, fill 0 if unknown and allowed


Input window hydro generation
Contents
Main dimensions
Additional variables
Propeller data
User profile
Optional inputs
Run method
Prop data
B4-70
Prop diameter
0
m
Number of props
0
#
AeA0
0
-
Cd
0
-
Generator type
Integrated
Drive type
-
Thruster type
-
Thruster type
-
Wake
0
-
Save
If wake is still unknown fill in suggested value based on hydro generator choice
If values are printed, input is correct and saved. If not, check if dot is used instead of comma. All values are required, fill 0 if unknown and allowed


Input window hydro generation
Contents
Main dimensions
Additional variables
Propeller data
User profile
Optional inputs
Run method
Interesting speed
0
kts
Save
If values are printed, input is correct and saved. If not, check if dot is used instead of comma. All values are required, fill 0 if unknown and allowed


Input window hydro generation
Contents
Main dimensions
Additional variables
Propeller data
User profile
Optional inputs
Run method
Rudder dimensions
C_root 0 m
C_tip 0 m
tc mean rudder 0 m
WSA rudder 0 m2
Keel dimensions
Volume keel 0 m3
C_root keel 0 m
C_tip keel 0 m3
tc mean keel 0 m
WSA keel 0 m2
T_max 0 m
VCB 0 m
Resistance overwrite
Upload data
If data is added, resistance is overwritten. Requires repetition for each run
Save
Optional inputs that provide a more accurate estimation of the resistance, if unknown leave as zero
If values are printed, input is correct and saved. If not, check if dot is used instead of comma. All values are required, fill 0 if unknown and allowed