Hybrid System Virtualisation For Predicting Performance And Eliminating Risks And Uncertainties

Amodio Palma[a] Stefan Goranov[a] Markus Wenig[a] Maciej Bendyk[a]
[a] *WinGD*

Abstract. Nowadays, the topic of hybrid marine energy systems is becoming increasingly relevant – this trend is mostly driven by the constant demand for safer and more efficient powertrains while being further accelerated by initiatives like zero-emission shipping [1], the initial IMO GHG 2050 strategy [2] or such instruments as EEDI, EEXI or CII [3] [4]. In this respect, the present study focuses on the domain of ocean-going vessels propelled by large 2-stroke marine engines and, in particular, on the challenges of a properly integrated propulsion system [5]. Virtualising the integrated system, using transient-capable components models provides plausible quantitative figures about its performance and enables informed decisions at early stage. To this end, the paper highlights two findings – first, the importance of component "rightsizing" and, second, the necessity for intelligent operation of those components. Embarking on an analysis of a wide range of customer studies for various vessel types (PCTC, Container, LNGC, etc.) it is demonstrated how each use case may lead to another optimal solution. For instance, utilizing the power-take-off (PTO) functionality for genset replacement might be generally feasible but its efficacy, due to the interaction of main engine and shaft generator, depends highly on the intended vessel operation. Another example is the arguably inefficient peak shaving functionality which, if only applied in a suitable situation (e.g. for genset load balancing), still may provide benefit to the overall system efficiency. The paper remarks the importance of a virtual tool to support the hybridisation of marine vessels. Such tool allows for the identification of potential risks and criticalities in a very early stage as well as for reduction of calibration effort and risk of failure during commissioning.

Keywords. Marine, Hybrid, Virtualisation, Simulation, 2-Stroke, System integration, Energy optimization, Battery, Peak shaving.

1. WinGD virtual toolchain

1.1. Overview

WinGD has developed an in-house virtual toolchain to tailor a hybridised propulsion system for any 2S marine applications, which will be presented in this paper together with a real application case.
The purpose of the toolchain is to support the design and development of the hybrid system and to provide customers with data-driven decisions in the very early stages.

This virtual toolchain operates through different design stages with growing level of detail and complexity as the system development progresses. The feasibility study is carried out in the first stage with the analysis of the project specifics followed by the initial layout and components sizing of the hybrid system. Since the components

rightsizing is key to obtain an optimal CapEx-OpEx trade off and maximise the return of investment this process is performed as integral part of the feasibility study.
To this end, WinGD has developed a fast-running sizing optimiser (SizOp) that provides a preliminary sizing of the components based on high level project data.
SizOp also provides GHG and OpEx figures particularly comparing the preliminary hybrid solution to a conventional configuration operating in the same conditions.
After the pre-sizing of the hybrid system and the assessment of the environmental and economic potentials the components are then integrated and operated in a virtual physical environment with high accuracy, plausibly replicating the behaviour of the actual hybrid system.
In a third step, usually at the project implementation, the components of the hybrid system are modelled in a detailed way to replicate more dynamic scenarios and fine-tune the energy management controller. This allows to identify potential risks and criticalities in a very early stage as well as to reduce the calibration effort and risk of failure during commissioning.

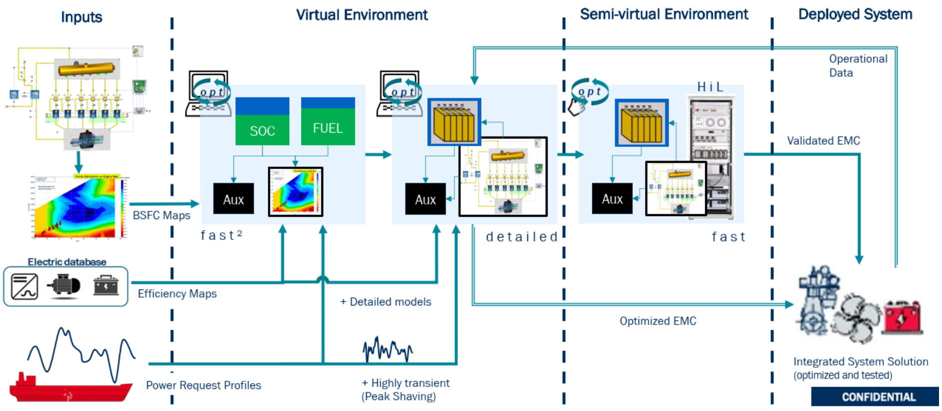

Figure 1. WinGD virtual toolchain

The present paper provides an overview of the first steps of the toolchain with a major focus on the operation of the hybrid system in the virtual environment. The process is illustrated through a real case scenario concerning the rightsizing and optimization of the system for a 2000 TEU feeder container.

1.2. Sizing Optimiser SizOp

"SizOp" was developed by WinGD in Matlab-Simulink environment where a fast-running algorithm provides the initial "skimming" of components sizes.
The tool requires a certain number of high-level project data, such as ship type and size, ship speed, etc.
SizOp operates a map-based virtual system where a pre-defined and application-specific control strategy is implemented. The virtual system is fed with a static profile obtained and scaled from existing ships' data, collected in a confidential database.

The map-based hybrid system is represented in a preliminary layout and parametrised in the components of shaft generator and battery. The size of these two components is varied in a specific range and a ‘design of experiment’ (DOE) simulation is conducted. The obtained DOE results are compared with those of a conventional system operating in the same conditions.
Some typical results of a SizOp calculation are shown in Figure 2 where a hybrid application with SG + battery is compared with a conventional system operating in the same conditions. The calculation yields a contour representation of GHG emission for different sizes of SG and battery, which are explored and applied to the hybrid system.

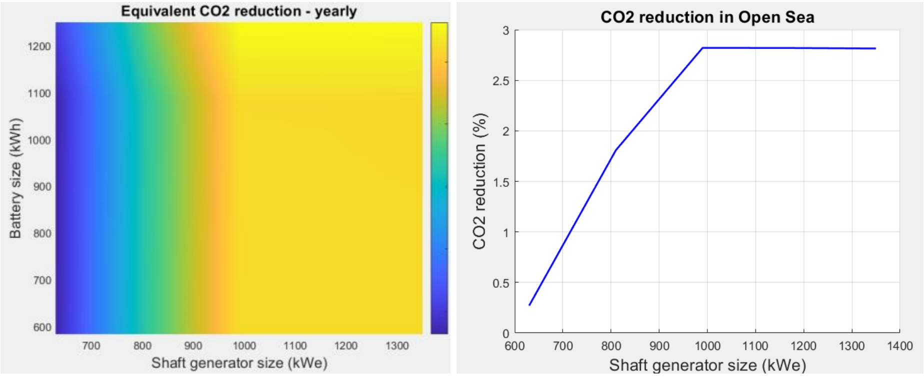

Figure 2. SizOp plotted results

With SizOp’s results the dimensions of the main electric components are effectively narrowed down to specific ranges that can be refined in the following stage of the toolchain. At this stage more detailed simulation models are used, and investigations are conducted in a GT-Suite environment. GT-Suite is a commercial software developed by Gamma Technologies, widely considered the industry-leading simulation tool with capabilities and libraries aimed at a wide variety of applications and industries.

1.3. Hybrid virtual platform

Once the hybrid layout and the components size are pre-defined, the system is then virtualised using a full system simulation platform. Here the physical models of all the components are integrated and operated in a virtual environment with high accuracy. The virtual platform is the second step of the toolchain and requires more detailed project data, such as electric load balance, operational profiles and propulsion request. This process provides a refining of the system sizing and more precise figures of fuel consumption, GHG emissions and OpEx.
Key aspect of the virtual platform is the system being operated with a more detail energy management that optimises the energy flux at every time-step to achieve specific objectives such as minimum fuel consumption / emissions and preservation of battery life.
The purpose of the GT simulation platform is to refine the hybrid layout and the sizing of the components as well as tuning the best control strategy for the system.

The chapter 2 will show a real-world application of the virtual platform for a 2000 TEU Feeder container with CPP propeller.

2. Case study: 2000 TEU Feeder Container with CPP

The case study presented in this paper is a 2000 TEU Feeder Container with 350 FEU and CPP propeller travelling in the Baltic and North Sea. The corresponding operational profile is shown in Figure 3.

	Sea passage			Canal			Port	
	Full	Optimal	Economic	Transit		Waiting	Manoeuvring	Idle
Speed	17.0 (18-16)	14.5 (16-12)	10.5 (12-8)	9.0	5.0	0.0	5.0	0.0
Time %	7 %	29 %	10 %	1 %	8 %	1 %	1 %	42 %

Figure 3. 2000 TEU Feeder Container profile

Purpose of the study was to provide an optimal hybrid solution that minimises GHG emission and OpEx.
Further customer requirement was to keep the generator-sets off at all sea conditions, including ports departing and arrival, while still providing continuity and safety of operation.

2.1 System layout definition

Based on the electric load balance, propulsion request and available engine power, the preliminary sizing optimization algorithm provides a battery capacity of at least 750 kWh and 2 potential shaft generator sizing solutions:

- 2.1 MWe
- 2.3 MWe

However only a minimum SG size of 2.3 MWe allows to fulfill the gensets-off requirement, therefore the hybrid layout chosen for this ship is represented in Figure 4. This solution shows also potential for reducing the installed gensets of at least 1 unit.
With the selected components the system is then virtualised and operated in the requested conditions of propulsion and electric loads. The virtual platform is fed with instantaneous profiles from real and similar ships scaled to the conditions of this 2000 TEU container ship application. In each condition the virtual system is integrated with the WinGD hybrid control that operates and optimise the system as a whole to achieve minimum fuel consumption, OpEx and battery life preservation.

Vessel Particulars	• Type: 2'000 TEU Feeder Container • Propeller Type: CPP • Reefer Containers • Ice class 1A
Main Engine	• 6X62DF • CMCR 12'600 kW @91 RPM - CSR 11'340 kW at 17.6 knots w/15% SM
Auxiliary Generating Sets	• 3DF x 1'100 kW • Reefers: 3.4 kW x350 FEU = 1'190kW • Electric loads as shared by SDARI
Shaft Generator	• 1x 2'300 kWe
Energy Storage System	• Battery 750 kWh
Thruster	• 1'200 kW
Shore Connection	• Optional

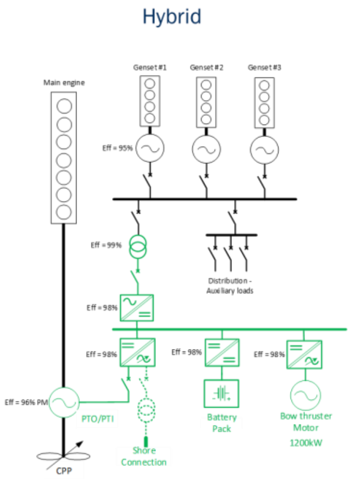

Figure 4. Hybrid system layout

2.2 SG sizing and operation with CPP

As shown in this paragraph, there are some benefits related to the combination of hybrid system and CPP type of propeller. This configuration influences directly the SG sizing and adds a further degree of freedom for the control system to optimise.

While the baseline operating points are laying on the combinatory curve (yellow line in figure 5) of the main engine map, the hybrid points can potentially move vertically as well as horizontally depending on the amount of power transferred to the SG and the pitch angle.

If this was an FPP case, the hybrid configuration would allow only a vertical shifting of such points on the engine map by controlling the SG torque share. However, the main engine torque-limit curve (red line) would cap the maximum power available for SG in fact limiting the maximum size choice for the SG - substantially, there is no point in sizing the SG to a power that cannot be provided by the main engine.

The configuration with CPP instead, allows a horizontal shift towards larger RPM conditions via pitch change. Here more power is available from the main engine which grants a larger margin for SG sizing. Such RPM increase can be also used to extend the shaft generator range of operation to lower ship speeds.

In addition to that, the pitch angle can also be optimised in relation to the "sweet spot" of the engine and obtain further fuel consumption reduction. The Figure 5 represents such "double-step" shift allowing to operate the engine in a much more efficient BSGC area compared to the conventional case.

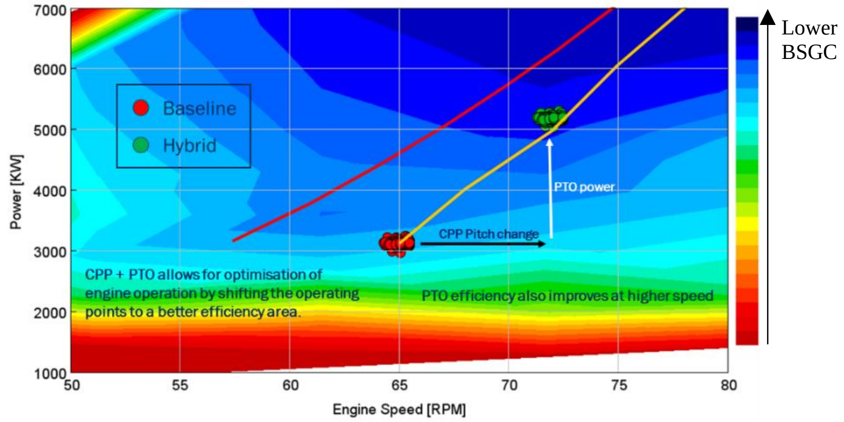

Figure 5. Engine points shifting with Shaft Generator + CPP

2.3 Battery sizing & operation

While the PTO size and optimisation regards mostly continuous operation at sea going with large impact on GHG emissions, gensets maintenance and OpEx, the sizing and use of battery influences three main aspects at both design and operation levels:

1. Installed electrical power on-board (gensets) – System Design
2. System stability and its transient response – System Operation
3. Intelligent peak shaving – System Operation

As stated before, a key requirement for the 2000 TEU feeder container project was to switch off the gensets during all the operation at sea, including port departure and arrival with bow thrusters. Compatibly with the cargo operation load request, such configuration would allow <u>the removal of at least 1 genset unit</u> which would significantly contain the capital expenditure for the hybrid solution.
To proceed with the sizing of the battery, it is necessary to study the dynamic behaviour of the electric loads during port departure and arrival. For a 2000 TEU feeder container approaching port with all reefers on, this looks like the Figure 6.

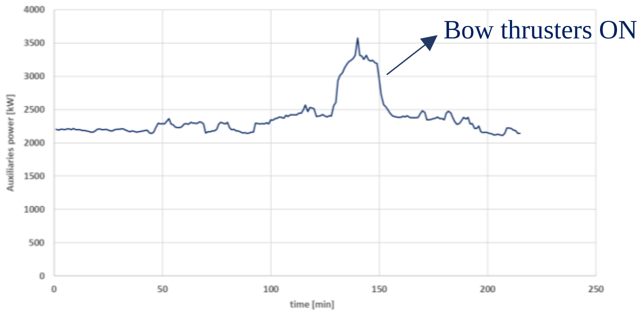

Figure 6. Auxiliary power w/ bow thrusters during maneuvering

Although the CPP enables the shaft generator at lower ship speeds, the electric peaks caused by the bow thrusters' operation are extremely challenging for the 2S engine and therefore cannot be fulfilled with the sole SG.
For this reason, the gensets could be kept off during the entire maneuver only if a sufficient battery capacity is installed.
Based on the profile of Figure 6 the battery was sized at a minimum capacity of 750 kWh. This means that any smaller batteries would require at least 1 gensets operating, whereas a larger battery would provide no real further benefit while increasing the project CapEx.

2.4 Virtual operation and simulation outcomes

The hybrid optimised layout selected for this 2000 TEU Feeder container project, represented in Figure 4, was simulated and compared with a virtualised conventional system operating in the same conditions.
The operation with SG brings two independent benefits:

- Electrical loads fulfilled with a more efficient source (M/E in place of gensets).
- Operating points shifted towards a more efficient BSGC/BSPC area of the engine fuel map.

The latter is particularly highlighted by the Figure 7.

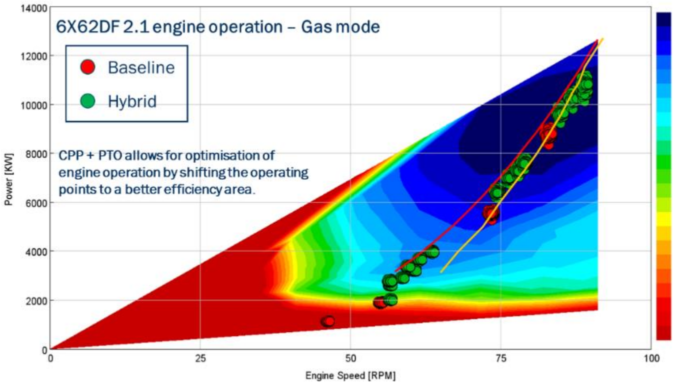

Figure 7. Operating point on main engine map for baseline and hybrid

The results of the simulative study are briefly summarized in Table 1, where the hybrid solution is compared to a conventional one (or baseline). For this 2000 TEU Feeder Container the hybrid solution proposed allowed for about 9% GHG emission reduction yearly, which goes up to 30% during maneuvering operation compared to a conventional system. In addition to that, the gensets can be kept always off during all the ship operations at sea allowing a significant reduction of 64k $ for the yearly maintenance costs of the gensets.

Table 1. Comparison between hybrid solution and conventional case for the 2000 TEU feeder container

System	Baseline	Hybrid	Δ
Engine	6X62DF	6X62DF	None

Shaft generator	None	2’300 kWe PTO	+2’300 kWe PTO
Battery	None	750 kWh	+750 kWh
Gensets	4x 1’100 kWe	3x 1’100 kWe	-1 Gensets unit
GHG emissions	16’545 ton/year	15’102	-8.7%
LNG	5’075	4’842	-4.6%
MDO	54	49	-8.8%
Methane slip	89	64	-28.2%
Fuel cost	2’561’800 $/year	2’443’050	-118’750
Gensets Maintain.	95’301	31’070	-64’231
OpEx	2’657’101	2’474’120	-182’981

3. Further case studies

Several further case studies have been carried out by WinGD concerning different ship types and sizes where the simulative toolchain was adopted. For brevity they are not detailed in this paper.

In Table 2 the Feeder Container case shown in detail in this paper is reported and compared with two different applications, showing the different component sizes and benefits compared to the respective conventional systems. The very different hybrid systems as well as GHG and OpEx benefits highlight the importance of tailoring the system layout to the specific application and that there is no “one fit all” solution.

Table 2. Comparison among optimal hybrid solutions for different applications

System	2k Feeder Container	174k LNG Carrier	7k PCT Carrier
Engine	6X62DF	2x 5X72DF	7X62DF
Shaft generator	2’300 kWe PTO	2x 1’200 kWe PTO	1’600 kWe PTO
Battery	750 kWh	-	-
Gensets	3x 1’100 kWe	2x 3’840 kWe 2x 2’880 kWe	3x 1’423 kWe
GHG reduction	8.7 %/year	1.8	9
OpEx reduction	182’981 $/year	128’037	215’208

4. Conclusions

The hybridisation of a marine propulsion and electric system is a multi-domain problem with several possible solutions in terms of layout and operation. WinGD has developed a virtual toolchain that tackles the challenges connected to the hybrid system rightsizing and its optimal operation. The toolchain provides data-driven answers to key questions in the very early stage of the design, particularly:

- Energetic and economic feasibility of the hybrid system.
- Rightsizing of the components.
- Operational efficiency.
- Safety.
- ROI and future-proof solutions.

To properly tackle these aspects, it is required a deep investigation of the project. The added value of the WinGD toolchain lays in the virtualisation, detailed modeling and integration of all the hybrid components, particularly the 2S engine. Being the most efficient and dominant power source on board the 2S engine represents the core of the system. Therefore, the detailed knowledge of its steady and dynamic behaviour is key to design a safe and efficient hybrid system.

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