PROCEEDINGS OF ECOS 2026 - THE 39TH INTERNATIONAL CONFERENCE ON

EFFICIENCY, **C**OST, **O**PTIMIZATION, **S**IMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS

28 JUNE – 03 JULY, 2026, CONSTANTA, ROMANIA

Integrated Multiphysics Modelling of Marine Vessel Energy Systems for Mission-Based Simulation

***Bashar Zebian*[a]*, Michel Alhajjar*[b]*, Rabih Al Haddad*[a]*, Chakib Bouallou*[a]*, Charbel Mansour*[b] *and Maroun Nemer*[a]**

[a] *Mines Paris-PSL, Center for Energy, Environment, and Processes, Versailles, France,*
bashar.zebian@minesparis.psl.eu, CA
[b] *Argonne National Laboratory, Vehicle and Mobility Systems Department, Lemont, United States,*
malhajjar@anl.gov

Abstract:

This paper presents a methodology for the development of a fully integrated multiphysics model of a marine vessel, enabling the consistent representation of propulsion, electrical, and thermal subsystems within a unified simulation framework. The approach is implemented in MATLAB/Simulink using a modular architecture that preserves energy consistency across propulsion, electrical, and thermal domains. The model is applied to a conventional ferry configuration to analyze system-level energy behavior under realistic operating conditions. The results demonstrate that propulsion, electrical, and thermal subsystems are strongly coupled and cannot be accurately assessed independently. Electrical loads, particularly HVAC systems, represent a significant share of the total demand, while thermal system performance is closely linked to propulsion operating conditions. Waste heat recovery contributes effectively during steady operation but is limited during low-load phases, requiring support from auxiliary systems. These findings highlight the importance of integrated modeling for accurately assessing vessel energy consumption and provide a flexible framework for the analysis of different vessel configurations.

Keywords:

Energy systems integration; HVAC systems; Marine vessels; Multiphysics modeling; Ship propulsion.

1. Introduction

1.1. Context and background

Modern marine vessels rely on several onboard energy systems that operate simultaneously to ensure safe and efficient operation. The propulsion system provides the mechanical power required to move the vessel through the water, while the electrical system supplies energy to a wide range of auxiliary equipment including navigation systems, lighting, refrigeration units, pumps, and HVAC components. In parallel, thermal systems regulate heating and cooling demands on board and can recover part of the waste heat produced by propulsion machinery. The overall energy consumption of a vessel therefore depends on the combined operation of these interconnected subsystems.

In practice, these systems are strongly coupled. Variations in propulsion load influence engine operating conditions, which directly affect fuel consumption as well as the amount of heat available in exhaust gases and cooling circuits. This thermal energy can then be partially recovered and used to supply onboard heating demands such as cabin climate control or domestic hot water production. At the same time, electrical consumption evolves continuously depending on operating conditions, environmental factors, and passenger activity. HVAC systems in particular can represent a significant share of auxiliary electrical demand. Because of these interactions, analyzing propulsion, electrical, and thermal systems separately may not accurately represent the overall energy behavior of the vessel.

Ferries provide a particularly relevant case for studying these interactions. Unlike deep-sea vessels that often operate at relatively constant speeds, ferries typically follow short and repetitive routes characterized by frequent acceleration, cruising, maneuvering, and docking phases. These operational patterns lead to rapidly changing propulsion power demand while electrical and thermal loads evolve simultaneously depending on passenger occupancy and environmental conditions. Accurately representing the energy performance of ferry systems therefore requires simulation tools capable of capturing the dynamic interactions between propulsion, electrical, and thermal subsystems under realistic operating profiles.

1.2. Literature review and research gap

Existing research has extensively addressed individual aspects of ship energy systems, particularly propulsion performance and hydrodynamic behavior [1–3]. These studies provide well-established methods for predicting propulsion power and efficiency but mainly focus on mechanical and hydrodynamic aspects. Thermal energy management has also been investigated, especially through waste heat recovery systems ([4],[5]). While these approaches demonstrate the potential of thermal energy reuse, they typically rely on steady-state thermodynamic analyses and do not capture the dynamic interactions between onboard systems. More recent studies highlight that propulsion, electrical, and thermal systems are often modeled independently [6–8], limiting the ability to represent system-level interactions during realistic vessel operation.

To address this limitation, the present work proposes a structured methodology for developing a fully integrated multiphysics model of a marine vessel capable of capturing the dynamic interactions between propulsion, electrical, and thermal subsystems. The modeling framework is implemented in MATLAB/Simulink using a modular architecture inspired by bond graph theory, which allows a consistent representation of energy exchanges across mechanical, electrical, and thermal domains [9]. The proposed approach is applied to the simulation of a ferry operating under a realistic mission profile in order to analyze system-level energy flows and subsystem interactions during dynamic operation.

The remainder of the paper is organized as follows. Section 2 describes the integrated multiphysics modeling framework and presents the development of the propulsion, electrical, and thermal subsystem models. Section 3 introduces the ferry case study and the operational mission profile used for simulation. Section 4 presents the simulation results and discusses the interactions between the different onboard energy systems. Finally, Section 5 summarizes the main conclusions of the study.

2. Methodology

This section presents the modeling methodology used to develop the integrated multiphysics simulation framework. The objective of the model is to reproduce the dynamic interactions between propulsion, thermal, and electrical systems during vessel operation while maintaining a consistent representation of energy flows across the different physical domains.

The modeling framework was implemented in MATLAB/Simulink, where each subsystem of the vessel is represented as a modular component with clearly defined inputs and outputs. This modular structure allows the individual development and validation of subsystem models while preserving the interactions necessary to represent the behavior of the complete vessel. The resulting model integrates propulsion dynamics, onboard thermal systems, and electrical energy distribution within a unified simulation environment.

The modeling process follows three main steps. First, the overall vessel energy architecture is defined and decomposed into propulsion, thermal, and electrical subsystems. Second, mathematical models are developed for each subsystem using a combination of physics-based equations and map-based component models. Finally, the subsystems are integrated within the simulation environment and driven by realistic operational profiles representing vessel speed and trajectory.

An overview of the modeling approach adopted in this work is illustrated in **Figure 1**.

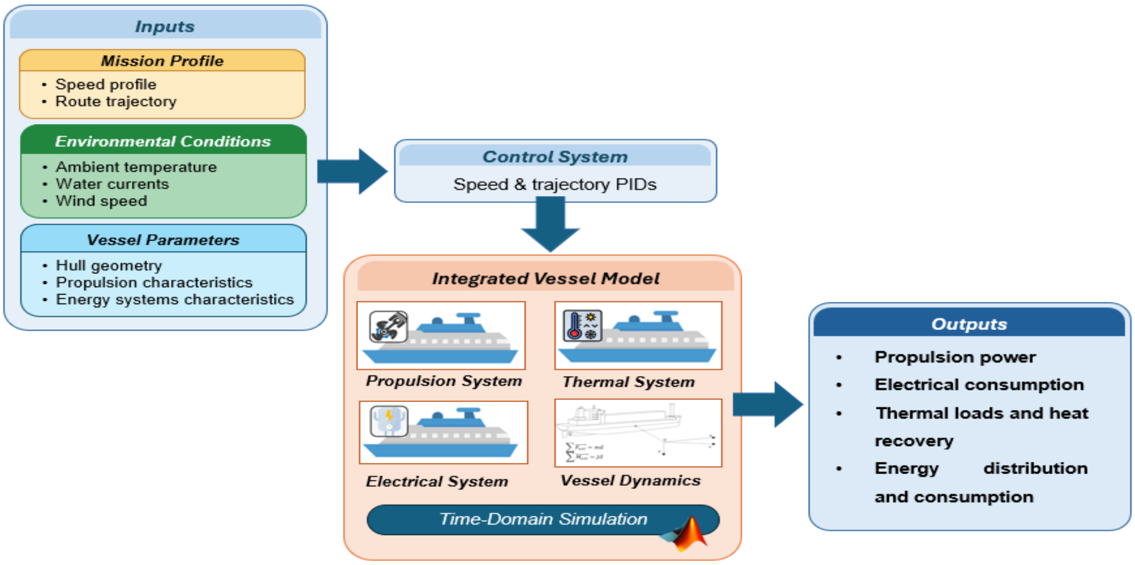

Figure 1. *Overview of the integrated multiphysics modeling framework.*

2.1. Modeling framework and architecture

The vessel model is developed using a system-level modeling approach in which propulsion, thermal, and electrical subsystems are represented within a unified simulation environment. The modeling philosophy follows an energy-based representation inspired by bond graph theory, which enables consistent coupling between mechanical, electrical, and thermal domains.

Within this framework, the vessel is described as a network of interacting components exchanging power through effort and flow variables whose product corresponds to instantaneous energy transfer [9]. This representation ensures that energy exchanges between subsystems remain physically consistent throughout the simulation. The resulting model captures the sequence of energy conversions occurring onboard the vessel, from the primary propulsion source to the hydrodynamic interaction with the surrounding water, while simultaneously accounting for auxiliary electrical loads and thermal energy recovery processes. Each subsystem is implemented as a modular block within the Simulink environment, allowing the model to remain flexible and scalable. This structure enables the integration of different propulsion architectures within the same simulation framework, including both conventional mechanical propulsion and alternative configurations such as electric powertrains.

Modern ships rely on several interconnected systems to satisfy their operational energy demands. These demands can generally be grouped into three main categories: propulsion power, auxiliary electrical power, and auxiliary thermal power [10]. **Figure 2** illustrates the energy system architecture adopted in this work, showing the interactions between propulsion components, electrical consumers, thermal systems, and vessel dynamics.

Understanding how mechanical, electrical, and thermal energy flows are distributed across these subsystems is essential for representing vessel operation within an integrated simulation environment.

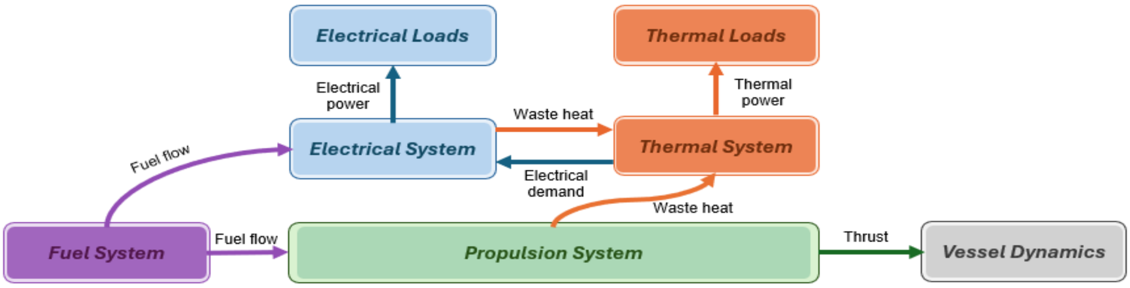

Figure 2. *Integrated vessel energy system architecture.*

2.2. Subsystem model description

Following the bond graph theory, the model is decomposed into several subsystems, each built in a library. The developed model considers the ship's three energy systems. Each energy system is described in the upcoming paragraphs.

2.2.1. Propulsion system model

The propulsion subsystem represents the conversion of onboard energy into mechanical power delivered to the propeller. Within the integrated vessel model, the propulsion system is responsible for generating the thrust required to overcome hydrodynamic resistance and maintain the prescribed operational speed. The propulsion framework includes the prime mover, the shaft transmission, and the propeller, and it interacts dynamically with the vessel motion model through thrust and rotational speed. This modular formulation allows the same propulsion structure to be used for both conventional and electric ferry configurations.

The conventional propulsion system architecture implemented in Simulink is illustrated in **Figure 3**.

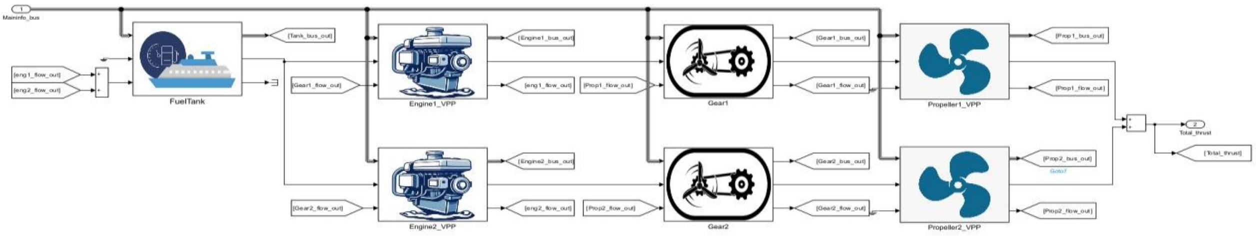

Figure 3. *Conventional propulsion system architecture.*

- **Prime mover model**

  In the conventional ferry configuration, propulsion is provided by diesel engines connected to fixed-pitch propellers through a transmission component. The engine output torque is determined from the throttle command using interpolation between characteristic torque curves representing constant-torque and wide-open-throttle operating conditions [11]:

$$T_{out} = (1 - T_{cmd})T_{CTT} + T_{cmd}T_{WOT} \tag{1}$$

  Fuel consumption is obtained from engine thermodynamic performance maps expressed as a function of engine torque and rotational speed as shown in **Figure 4**.

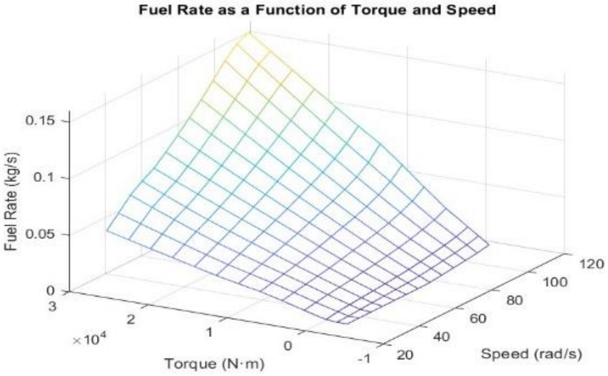

Figure 4. *Fuel map as function of the engine speed and torque.*

For the electric ferry configuration, the diesel engine is replaced by a battery energy storage system and an electric propulsion motor. Electrical energy from the battery is converted into mechanical torque through a motor drive system. The motor torque is controlled to satisfy the propeller load demand.

The battery model captures the state-of-charge evolution and internal electrical behavior, while the electric motor model represents electromagnetic torque generation and associated losses. This modeling approach enables accurate representation of electric propulsion performance during varying load conditions and mission profiles.

- **Shaft dynamics**

  The drivetrain transmits torque from the prime mover to the propeller through a transmission shaft system. The rotational dynamics of the shaft are governed by [12]:

$$T_{shaft} - T_p = \sum I \, \dot{\omega_{prop}}, \tag{2}$$

  The transmission converter establishes the relation between engine and propeller rotational speeds [13]:

$$\dot{\omega}_e = \dot{\omega}_{prop} \, K, \tag{3}$$

  where K is the transmission ratio.

- **Propeller hydrodynamic model**

  The propeller converts the rotational mechanical power delivered by the shaft into hydrodynamic thrust acting on the vessel hull. In order to represent the propeller behavior under varying operating conditions, a four-quadrant fixed pitch propeller model is implemented. This formulation enables the prediction of thrust and torque over the full operating envelope.

  In this study, the propeller hydrodynamic coefficients are expressed as functions of the advance angle (β) using a Fourier series representation [14]. The thrust and torque coefficients are therefore written as:

$$C_t(\beta) = \sum_{k=0}^{k_{max}} (A_t(k)\cos(\beta k) + B_t(k)\sin(\beta k)), \tag{4}$$

$$C_q(\beta) = \sum_{k=0}^{k_{max}} \left(A_q(k)\cos(\beta k) + B_q(k)\sin(\beta k)\right), \tag{5}$$

$$\beta = \arctan\left(\frac{V_a}{nD}\right), \tag{6}$$

  Once the thrust and torque coefficients are determined, the delivered thrust and absorbed torque of the propeller are calculated as [15]:

$$T_p = \rho D^2 C_t\left(V_a^2 + (Dn_{prop})^2\right), \tag{7}$$

$$Q_p = \rho D^3 C_q\left(V_a^2 + (Dn_{prop})^2\right), \tag{8}$$

  The resulting propeller characteristics used in the simulation are shown in **Figure 5**, which illustrates the variation of thrust and torque coefficients with the advance angle.

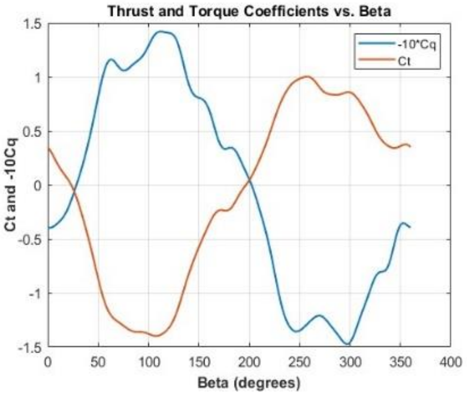

Figure 5. *Propeller four quadrant curve versus advance angle.*

2.2.2. Vessel dynamics model

The vessel dynamics module describes the motion of the ferry under the combined action of propulsion forces, hydrodynamic loads, rudder forces, and environmental disturbances. The ship motion is modeled using Newton's second law applied to the rigid-body dynamics of the vessel. The equations of motion governing surge, sway, and yaw motions are expressed as [15]:

$$(m + m_x)\dot{u} - \left(m + m_y\right)vr - x_G m r^2 = X, \tag{9}$$

$$\left(m + m_y\right)\dot{v} + (m + m_x)ur + x_G m\dot{r} = Y, \tag{10}$$

$$(I_z + x_G^2 m + J_z)\dot{r} + x_G m(\dot{v} + ur) = N, \tag{11}$$

- **Resistance model**

  The total resistance acting on the vessel is composed of calm-water, hydrodynamic, and aerodynamic components.

$$R_{tot} = R_{cw} + R_{hyd} + R_{aero}, \tag{12}$$

  The calm-water resistance R_{cw} is calculated using the Holtrop–Mennen method, which provides empirical correlations for predicting ship resistance based on hull geometry and operating conditions ([1], [16]). This method is widely used for ship performance analysis and propulsion prediction.

  Hydrodynamic maneuvering forces are represented using hydrodynamic derivatives obtained from standard maneuvering models and numerical estimation procedures. Hydrodynamic resistance R_{hyd} represents the forces generated by the interaction between the hull and the surrounding water during maneuvering conditions. These forces are expressed using hydrodynamic derivatives obtained from standard maneuvering models and numerical estimation procedures [15]. Those forces are expressed as:

$$X_{hydro} = 0.5\,\rho\,V_{nav}^2\,L\,T\,X'_H, \tag{13}$$

$$Y_{hydro} = 0.5\,\rho\,V_{nav}^2\,L\,T\,Y'_H, \tag{14}$$

$$N_{hydro} = 0.5\,\rho\,V_{nav}^2\,L^2\,T\,N'_H, \tag{15}$$

  Wind acting on the exposed surfaces of the vessel generates additional forces R_{aero} that influence ship motion. The aerodynamic forces are modeled as:

$$X_{wind} = 0.5\,\rho_{air}\,V_{rel}^2\,A_T\,C_x, \tag{16}$$

$$Y_{wind} = 0.5\,\rho_{air}\,V_{rel}^2\,A_L\,C_y, \tag{17}$$

$$N_{wind} = 0.5\,\rho_{air}\,V_{rel}^2\,A_L\,L_{OA}\,C_N, \tag{18}$$

  C_x, C_y, and C_N are aerodynamic coefficients determined using Isherwood or Blendermann methods [17].

- **Rudder model**

  The rudder plays a major role in controlling the vessel trajectory by generating lateral forces and yaw moments. The rudder forces, incorporated into the dynamic equations to model the vessel's manoeuvring behaviour, are expressed as [15]*:*

$$X_{rud} = -F_N \sin\,\delta, \tag{19}$$

$$Y_{rud} = -(1 + a_H)F_N \cos\delta, \tag{20}$$

$$N_{rud} = -(1 + a_H)x_R F_N \cos\delta, \tag{21}$$

2.2.3. Thermal system model

The thermal subsystem represents the onboard heat management processes required to maintain acceptable cabin conditions and supply domestic hot water during vessel operation. In ferry vessels, thermal demands are mainly associated with cabin climate control and auxiliary heating requirements, which vary depending on environmental conditions, passenger occupancy, and operating phases. Because thermal loads interact with both propulsion waste heat and electrical consumption through HVAC systems, their representation is necessary for capturing the complete onboard energy balance. The thermal system model developed includes three main components: the cabin thermal zone, the HVAC system, and the waste heat recovery system.

- **Cabin and HVAC model**

  The passenger cabin is represented as a single thermal zone in which the internal air temperature evolves according to heat exchanges with the surrounding environment and internal heat gains from passengers and onboard equipment. Heat transfer mechanisms considered in the model include conduction through the vessel structure, convection with external air, radiation effects, and internal heat gains generated by passengers.

  The HVAC system is modeled using a vapor compression cycle, where the compressor power is calculated based on the cooling load and the coefficient of performance (COP). The thermal demand is determined from the cabin energy balance, accounting for heat gains due to passengers, onboard equipment, and environmental conditions. The model captures the dynamic interaction between cabin thermal loads and electrical consumption through the HVAC system.

  The cabin thermal behavior and HVAC operation are modeled following established approaches commonly used in vehicle thermal management studies. The formulation adopted in this work is based on the methodologies presented by ([18], [19], [20]). These references provide validated formulations for estimating cabin thermal loads and air thermodynamic properties.Because HVAC systems operate continuously throughout vessel operation, they represent a significant portion of the auxiliary electrical demand and therefore influence the overall vessel energy consumption.

- **Waste heat recovery system**

  The vessel propulsion system produces a considerable amount of thermal energy in the form of exhaust gases and engine cooling water. This energy can be partially recovered and reused to supply onboard heating demands through a waste heat recovery system.

  In the present model, a closed water loop is used to transfer heat recovered from engine exhaust gases and cooling circuits to the cabin heating system and domestic hot water supply. The overall architecture of the waste heat recovery system implemented in the simulation framework is illustrated in **Figure 6**.

  The amount of useful heat recovered depends on both the heat available from the propulsion system and the instantaneous thermal demand of the vessel. When the recovered heat is insufficient to satisfy the heating demand, an auxiliary electric heater is used as a backup heat source to maintain the desired thermal conditions.

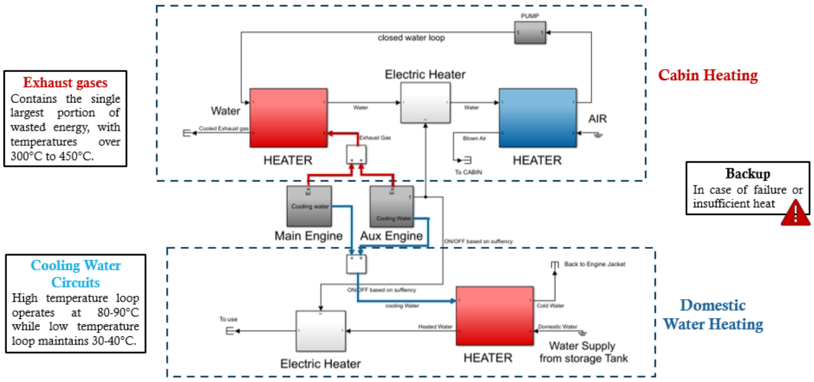

Figure 6. *WHRS architecture.*

2.2.4. Electrical system model

The electrical subsystem represents the onboard generation and consumption of electrical power required to operate auxiliary systems during vessel operation. Typical electrical consumers in passenger ferries include navigation equipment, lighting systems, refrigeration units, pumps, control electronics, and HVAC components. These loads evolve throughout the operating cycle and therefore contribute to the overall energy demand.

Electrical power is supplied by auxiliary diesel generator sets in which a diesel engine is mechanically coupled to a synchronous generator. The generator–engine coupling is represented through an efficiency-based relationship converting mechanical power from the auxiliary engine into electrical output power. The electrical distribution system is assumed to operate at a nominal voltage of 440 V, corresponding to typical shipboard electrical grids used in ferry vessels. Modeling approaches for marine auxiliary power systems follow the formulations described in ([10], [2], [19]).

A significant portion of the electrical demand originates from the HVAC system. The compressor power required by the vapor compression cycle is calculated from the cooling load obtained from the thermal model:

$$P_{compressor} = \frac{Q_{evap}}{COP}, \tag{22}$$

The COP varies with ambient conditions and therefore allows HVAC electrical demand to evolve dynamically during vessel operation. By representing both auxiliary electrical loads and their interaction with the thermal subsystem, the electrical model enables the integrated simulation framework to capture the coupling between propulsion operation, HVAC demand, and onboard electrical consumption.

Table 1. *Ferry appliance power.*

Appliance	Number	Power (kW/unit)
Navigation lights	10	0.05
Electrical Board	1	1.5
Refrigeration	1	10
Navigation Systems	5	1

2.2.5. System integration and control

After the individual subsystem models are developed and validated separately, they are integrated within a unified simulation framework to represent the coupled operation of propulsion, electrical, thermal, and vessel dynamics modules. The integrated model forms a closed-loop system in which energy flows and subsystem interactions evolve dynamically during vessel operation. The simulation framework is implemented in **MATLAB/Simulink**, where each subsystem exchanges information through structured signal buses representing propulsion variables, electrical loads, and thermal demands. The overall structure of the integrated simulation environment is illustrated in **Figure 7.**

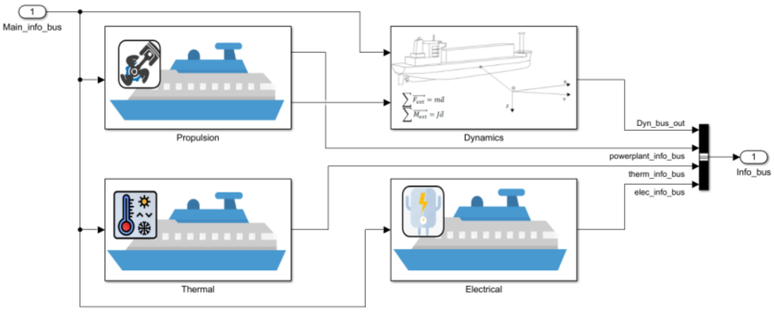

Figure 7. *The overall integration of the energy systems.*

Through this integration, propulsion power demand, auxiliary electrical loads, and thermal energy requirements continuously influence each other, allowing the model to reproduce realistic vessel behavior under varying operating conditions.

To ensure realistic vessel operation along a predefined mission profile, a navigation control system is implemented to regulate both vessel speed and trajectory. The control architecture consists of two proportional–integral–derivative (PID) controllers as illustrated in **Figure 8.** The velocity controller adjusts the propulsion command according to the difference between the desired speed and the actual vessel speed obtained from the dynamics model, while the trajectory controller generates the rudder angle required to follow the desired course over ground (COG).

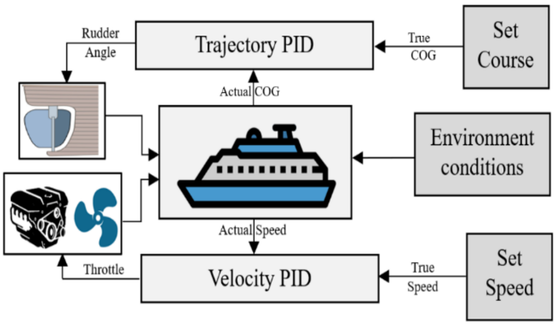

Figure 8. *Navigation control architecture.*

Environmental disturbances are incorporated to reproduce realistic operating conditions. Sea currents are introduced using velocity components obtained from Copernicus Marine Service datasets, defined as functions of time and vessel position. Wind disturbances are represented through wind speed and direction relative to the vessel heading, allowing aerodynamic forces to influence the vessel dynamics model.

3. Case study

The proposed modeling framework is applied to a conventional Ro-Pax ferry to evaluate the interactions between propulsion, electrical, and thermal subsystems under a realistic mission profile. The objective is to assess the ability of the integrated model to reproduce system-level energy behavior under dynamic operating conditions.

The considered vessel is configured with a twin-screw propulsion system consisting of two medium-speed diesel engines driving fixed-pitch propellers. The vessel main characteristics used in the simulation are summarized in **Table 2**.

The integrated simulation framework described in Section 2 is used to represent the vessel propulsion system, dynamics, electrical consumers, and thermal loads within a unified time-domain model.

Table 2. *Main characteristics of the conventional ferry.*

Parameter	Value
Vessel type	Ro-Pax mid-sized ferry
Propulsion system	Two diesel engines of 8 MW each
Passenger capacity	1040
Propellers	Fixed pitch of 3.9 m and 3.44 m diameter
Generator power	800 kW of 90% efficiency
Cabin volume	3115 m^3

4. Results and discussion

This section presents the results obtained from the simulation of the conventional ferry described in Section 3. The objective is to evaluate the ability of the proposed integrated modeling framework to reproduce realistic vessel behavior and to capture the interactions between propulsion, electrical, and thermal subsystems under operational conditions.

The vessel is simulated over a representative operating profile including acceleration, cruising, and deceleration phases. The results are analyzed in terms of propulsion performance, auxiliary energy demands, and overall energy consumption to highlight the impact of subsystem coupling.

4.1. Operating profile and vessel response

The operating profile used in the simulation is presented in **Figure 9(a)**, showing the reference vessel speed derived from publicly available AIS data provided by Washington State Ferries along with the simulated response. The results indicate that the implemented control system accurately tracks the desired speed profile throughout the different phases of operation, including acceleration, steady cruising, and deceleration. The mean tracking error remains below 5%, with higher deviations observed during deceleration phase due to transient dynamics and control limitations, which relies on natural hydrodynamic resistance rather than active braking.

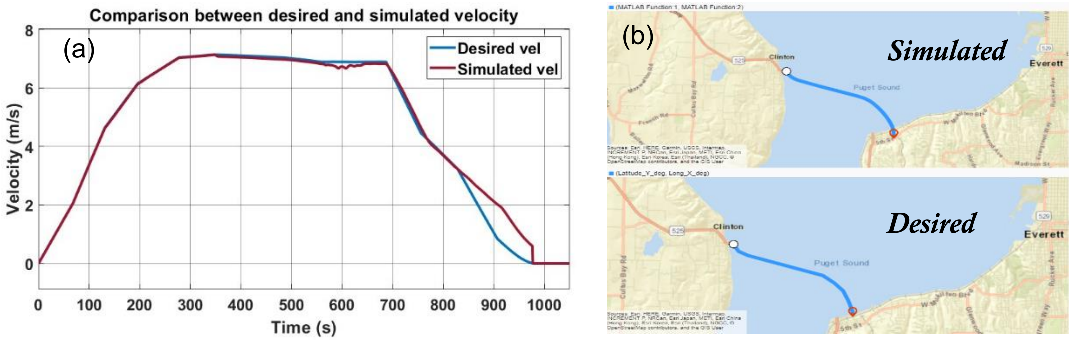

Figure 9. *Desired versus simulated profiles of the vessel versus time: (a) velocity; (b) trajectory.*

In addition to speed tracking, the vessel trajectory is evaluated to assess the performance of the navigation system. The trajectory tracking is performed in two dimensions using latitude and longitude coordinates, while the course over ground defines the vessel heading. The simulated trajectory closely follows the reference route as depicted in **Figure 9(b),** confirming the ability of the integrated model to reproduce realistic vessel motion under environmental disturbances.

4.2. Propulsion performance

The propulsion power demand corresponding to the operating profile is presented in **Figure 10(a)**. The results show that the propulsion system responds consistently to the different phases of vessel operation. During acceleration, the required power increases rapidly to overcome vessel inertia and hydrodynamic resistance, while a nearly steady power level is observed during the cruising phase. As the vessel decelerates, the propulsion power decreases as the vessel relies on natural hydrodynamic drag and drivetrain losses.

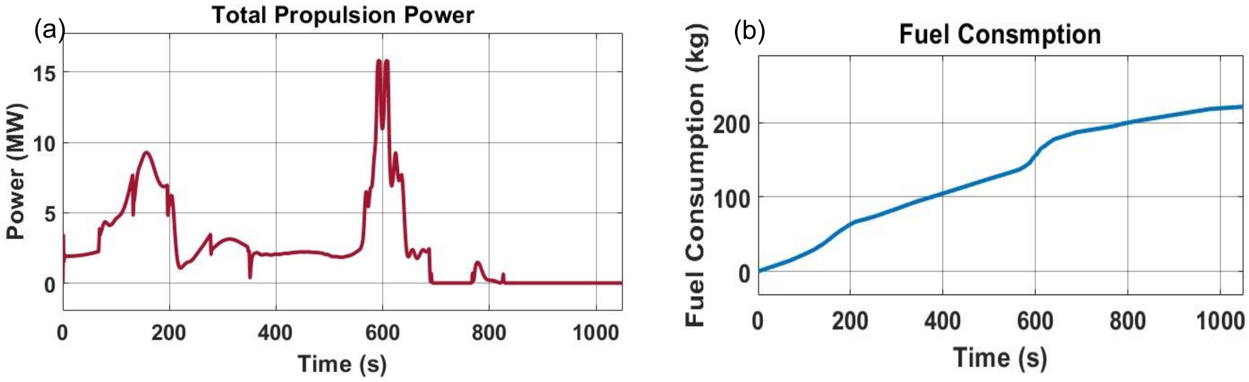

Figure 10. *(a) Propulsion power demand and (b) cumulative fuel consumption over the operating profile.*

Short-duration peaks in propulsion power can be observed during transition phases of the operating profile. These peaks are associated with transient control actions resulting from speed-tracking corrections. Despite these localized effects, the propulsion power remains within the installed power limits and the overall trend is consistent with typical ferry operation [2] confirming that the model provides a realistic representation of propulsion behavior.

Fuel consumption is evaluated over the operating profile based on the engine operating conditions presented in **Figure 10(b).** The results indicate a total fuel consumption of approximately 240 kg, corresponding to an equivalent rate of about 0.85 t/h ([21], [22]). These values are consistent with reported ranges for conventional ferries operating under similar conditions, further supporting the validity of the proposed modeling framework.

4.3. Electrical and thermal loads

The auxiliary energy systems are evaluated under a winter operating scenario, ensuring consistency with the propulsion results and enabling a coherent system-level analysis. In this context, the thermal demand is primarily driven by cabin heating requirements, while electrical consumption is influenced by both onboard appliances and auxiliary heating systems. For the present operating scenario, the ambient temperature is set to 6°C, and a cabin comfort band of 20–24°C is maintained.

Figure 11 presents the evolution of electrical and thermal energy flows over the operating profile. The thermal subplot illustrates the interaction between available waste heat from the propulsion system, the recovered heat, and the total thermal demand to heat the cabin and the domestic water needs, while the electrical subplot shows the decomposition of the total onboard electrical consumption into HVAC-related loads and other auxiliary loads.

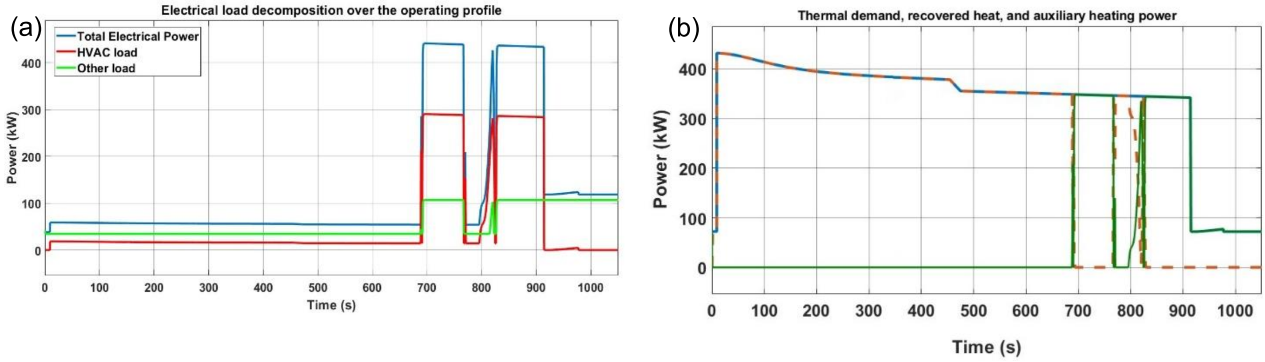

Figure 11. *Evolution of (a) electrical loads and (b) thermal demand and recovered heat over the operating profile.*

The thermal results highlight the strong dependency of the waste heat recovery system on propulsion operating conditions. During acceleration and cruising phases, the propulsion system operates at relatively high load, generating a significant amount of thermal energy in the exhaust gases and cooling circuits. Under these conditions, the recovered heat is sufficient to supply a large portion of the onboard heating demand, and the contribution of auxiliary heating remains limited.

However, during low-load phases such as deceleration and maneuvering, the propulsion system produces significantly less waste heat. As a result, the amount of recoverable heat decreases and becomes insufficient to meet the thermal demand. At these operating conditions, the engine runs at low load, resulting in reduced exhaust energy and limited heat recovery. In these periods, the auxiliary electric heater is activated to compensate for the deficit and maintain the required cabin temperature. This behavior demonstrates that the effectiveness of the waste heat recovery system is inherently linked to propulsion load and cannot ensure full thermal autonomy under all operating conditions.

This interaction directly impacts the electrical system. As shown in **Figure 11**(a), the activation of the auxiliary electric heater leads to a significant increase in HVAC-related electrical consumption. During these phases, the HVAC load becomes the dominant component of the total electrical demand, exceeding the contribution of standard onboard appliances.

During steady operating conditions, when waste heat recovery is sufficient, HVAC-related electrical consumption remains relatively low and the electrical demand is dominated by baseline loads. In contrast, when waste heat recovery becomes insufficient, the increase in HVAC demand results in a substantial rise in total electrical consumption, clearly illustrating the coupling between thermal and electrical systems.

5. Conclusion

This paper presented a structured methodology for the development of a fully integrated multiphysics model of a marine vessel, enabling the simultaneous representation of propulsion, electrical, and thermal subsystems within a unified simulation framework. The modeling approach, implemented in MATLAB/Simulink, ensures consistent energy exchanges across physical domains and allows the simulation of realistic vessel operation.

The proposed modeling framework was applied to a conventional ferry configuration operating under a representative mission profile. The results demonstrate that the model is capable of accurately reproducing propulsion behavior, vessel dynamics, and auxiliary energy demands while capturing the interactions between onboard systems.

The analysis highlights the strong coupling between propulsion, thermal, and electrical subsystems. In particular, the thermal system behavior is directly influenced by propulsion operating conditions through the availability of recoverable waste heat. During steady operating phases, waste heat recovery is able to supply a significant portion of the onboard heating demand, thereby reducing the reliance on auxiliary energy sources. However, during low-load phases such as deceleration and maneuvering, the reduction in engine load leads to a decrease in available waste heat, limiting the effectiveness of the recovery system.

As a consequence, auxiliary electric heating systems are activated to maintain cabin comfort conditions, which results in a significant increase in HVAC-related electrical consumption. Under these conditions, HVAC loads become a dominant component of the total onboard electrical demand, demonstrating that thermal system limitations directly influence electrical energy consumption.

Overall, these results confirm that waste heat recovery and HVAC systems cannot be analyzed independently, as their interaction plays a critical role in the onboard energy balance. The study demonstrates that integrated multiphysics modeling is essential for capturing the interactions between onboard energy systems and for providing realistic estimates of vessel energy consumption. The proposed framework provides a flexible and scalable tool for system-level analysis and can be extended to alternative propulsion architectures and operating scenarios in future work.

Acknowledgments

This work was sponsored by the U.S. Department of Energy (DOE) Office of Energy Dominance Financing (EDF) under the Advanced Technology Vehicles Manufacturing Loan Program. The submitted manuscript has been created in collaboration with UChicago Argonne, LLC, Operator of Argonne National Laboratory (Argonne). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

References

[1] J. Holtrop and G. G. J. Mennen, “An approximate power prediction method,” Netherlands Ship Model Basin, NSMB, Wageningen, Publication No. 689, Published in: International Shipbuilding Progress, ISP, Volume 29, Nr 335, 1982, 1982, Accessed: Jan. 30, 2024.

[2] J. S. Carlton, Marine propellers and propulsion, 2nd ed. Amsterdam: Butterworth-Heinemann, 2007.

[3] J. Kayano, H. Yabuki, N. Sasaki, and R. Hiwatashi, “A Study on the Propulsion Performance in the Actual Sea by means of Full-scale Experiments,” TransNav Int. J. Mar. Navig. Saf. Sea Transp., vol. 7, no. 4, pp. 521–526, Dec. 2013, doi: 10.12716/1001.07.04.07.

[4] M. Grljušić, V. Medica, and N. Račić, “Thermodynamic Analysis of a Ship Power Plant Operating with Waste Heat Recovery through Combined Heat and Power Production,” Energies, vol. 7, no. 11, pp. 7368–7394, Nov. 2014, doi: 10.3390/en7117368.

[5] C. A. Frangopoulos, “Developments, Trends, and Challenges in Optimization of Ship Energy Systems,” Applied Sciences, vol. 10, no. 13, p. 4639, Jan. 2020, doi: 10.3390/app10134639.

[6] E. A. Bouman, E. Lindstad, A. I. Rialland, and A. H. Strømman, “State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review,” Transportation Research Part D: Transport and Environment, vol. 52, pp. 408–421, May 2017, doi: 10.1016/j.trd.2017.03.022.

[7] F. Yilmaz and E. Sulukan, “ENERGY SYSTEM ANALYSIS AND MODELLING OF AN ELECTRIC POWERED FERRY,” Journal of Naval Science and Engineering, vol. 16, pp. 143–170, Nov. 2020.

[8] B. Taskar, K. K. Yum, S. Steen, and E. Pedersen, “The effect of waves on engine-propeller dynamics and propulsion performance of ships,” Ocean Engineering, vol. 122, pp. 262–277, Aug. 2016, doi: 10.1016/j.oceaneng.2016.06.034.

[9] D. C. Karnopp, D. L. Margolis, and R. C. Rosenberg, “System Dynamics: Modeling, Simulation, and Control of Mechatronic Systems, 5th Edition | Wiley,” Wiley.com. Accessed: Sep. 30, 2024.

[10] H. J. Klein Woud and D. Stapersma, “Design of Propulsion and Electric Power Generations Systems,” Published by IMarEST, The Institute of Marine Engineering, Science and Technology. ISBN: 1-902536-47-9, 2008, Accessed: Jan. 30, 2024.

[11] E. S. Islam, N. Kim, R. Vijayagopal, A. R. Transportation, P. S. Division, and A. N. Laboratory, “Vehicle Simulation Process to Support the Analysis for MY 2027 and Beyond CAFE and MY 2030 and Beyond HDPUV FE Standards,” 2023.

[12] M. H. Ghaemi and H. Zeraatgar, “Analysis of hull, propeller and engine interactions in regular waves by a combination of experiment and simulation,” J Mar Sci Technol, vol. 26, no. 1, pp. 257–272, Mar. 2021, doi: 10.1007/s00773-020-00734-5.

[13] “Gearbox Ratio,” AB Marine.2022

[14] F. Dupriez-Robin, “Dimensionnement d’une propulsion hybride de voilier, basé sur la modélisation par les flux de puissance,” phdthesis, Université de Nantes, 2010.

[15] H. Yasukawa and Y. Yoshimura, “Introduction of MMG standard method for ship maneuvering predictions,” J Mar Sci Technol, vol. 20, no. 1, pp. 37–52, Mar. 2015, doi: 10.1007/s00773-014-0293-y.

[16] J. Holtrop, “Holtrop - A Statistical Re-Analysis of Resistance and Propulsion Data.” Accessed: Sep. 30, 2024.

[17] Q. Chen, Q. Yin, A. Fan, X. Sun, and X. Mou, “Research on the calculation methods of wind load coefficients of inland cruise ship,” in 2015 International Conference on Transportation Information and Safety (ICTIS), Jun. 2015, pp. 871–876. doi: 10.1109/ICTIS.2015.7232159.

[18] F. Breque, “Etude et amélioration d’une pompe à chaleur pour véhicule électrique en conditions de givrage,” Theses, Université Paris sciences et lettres, 2017. Accessed: Mar. 19, 2026. [Online]. Available: https://pastel.hal.science/tel-03081279

[19] ASHRAE, “Knovel - 2009 ASHRAE Handbook - Fundamentals (I-P Edition).”

[20] R. A. Haddad, H. Basma, and C. Mansour, “Modeling and control of heat pump system for battery electric buses,” Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 236, no. 14, pp. 3201–3220, Dec. 2022, doi: 10.1177/09544070211069465.

[21] “Why do aluminium ferries have to go fast?,” CruiseandFerry.net.

[22] S. Martinić-Cezar, Z. Jurić, N. Assani, and B. Lalić, “Optimization of Fuel Consumption by Controlling the Load Distribution between Engines in an LNG Ship Electric Propulsion Plant,” Energies, vol. 17, no. 15, p. 3718, Jan. 2024, doi: 10.3390/en17153718.