Economic Potential Analysis of Energy Storage Systems in Wind-Propelled Vessels to Reduce Transit-Time Variability

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Abstract:

This paper assesses the techno-economic performance of a fully wind-propelled Handysize bulk carrier operating on the Hampton Roads (USA)–Rotterdam (NL) route for the transport of low-value, non-perishable cargoes. Previous analyses suggested potential economic competitiveness, but were limited in their ability to fully capture voyage time variability and its impact on freight costs.

In this work, routing simulations based on hourly wind reanalysis data are used to obtain yearly distributions of voyage duration for all departure dates. These are coupled with a freight calculation framework under a closed-fleet configuration. Results indicate that, despite longer and more variable transit times, wind-only propulsion can achieve comparable or lower freight costs than a conventional vessel for the case considered, even when accounting for fleet size adjustments.

An inventory-based model is used to quantify the impact of transit time on logistics costs. Pipeline inventory, driven by mean transit time, is found to dominate total cost, while variability plays a secondary role due to fleet aggregation effects. Reductions in both mean duration and dispersion lead to moderate savings, but not at a level that would clearly justify additional onboard systems.

For the case studied, the results suggest that reducing average transit time is more economically relevant than reducing variability, with implications for the valuation of onboard energy storage. Preliminary results suggest that a reversible propeller-turbine in combination with energy storage systems can reduce both average transit times and transit time variability.

Keywords:

Thermodynamics; Energy; ECOS Conference; Exergy; Sustainability.

1. Introduction

The decarbonization of maritime transport is one of the main technological and regulatory challenges facing the shipping sector in the current energy-transition context. Although most efforts have focused on alternative fuels and hybrid propulsion systems, recent years have seen renewed interest in fully wind-propelled configurations for certain cargo types, particularly those with low intrinsic value and limited time sensitivity.

In recent years, wind-assisted propulsion systems (WAPS) have attracted renewed interest at both the industrial and regulatory levels [1]. Several reports by the European Commission, through the European Maritime Safety Agency (EMSA), as well as technical studies promoted by the International Maritime Organization (IMO) and classification societies, have identified auxiliary wind devices—such as Flettner rotors, automated rigid sails, and wing sails—as technologies with significant potential to reduce fuel consumption in conventional ships [2].

The dominant approach in these studies considers wind propulsion as a complementary system intended to reduce the load on the main engine, essentially acting as an energy-saving device. Under this paradigm, the vessel retains a conventional propulsion architecture, while wind energy serves as a secondary source that reduces emissions and improves energy efficiency without substantially altering the operating model or the scheduled service speed.

However, the possibility of conceiving merchant vessels whose primary propulsion is exclusively wind-based has received comparatively less attention in recent technical literature.

In this context, the recent Master's thesis by Javier Sarmiento Gil, one of the authors, analyzed the techno-economic feasibility of a fully wind-propelled merchant vessel for the transatlantic transport of coal between Hampton Roads (United States) and Rotterdam (The Netherlands) [3]. The results show that, under a wide range of market scenarios, this solution can be economically competitive with a conventionally powered diesel vessel of equivalent size.

The analysis revealed a structural limitation inherent to wind propulsion: the high variability of transit time. Unlike mechanically propelled ships, whose service speed can be maintained relatively constant, sailing vessels are subject to meteorological variability and the seasonality of wind regimes, resulting in travel-time distributions with significant dispersion [3].

From a transport-economics perspective, comparison usually focuses on average costs per ton transported. However, from the perspective of an industrial importer operating under lean-manufacturing principles, transit-time variability has a direct consequence: the need to increase safety inventory to guarantee uninterrupted plant operation. This additional immobilization of capital represents a financial cost that is not usually incorporated explicitly into the feasibility analysis of maritime transport [4].

Within the POSEIDON project, reversible hydrokinetic generation and onboard energy storage solutions are being investigated which, in combination with the primary wind propulsion system, could help reduce transit-time dispersion and improve the operational predictability of the vessel [5]. Electricity generated during favorable sailing conditions may be stored by electrochemical systems or energy carriers such as hydrogen, thereby providing auxiliary power in periods of weak wind.

The aim of this work is to quantify, by means of a simplified model, the economic cost associated with transit-time variability in a transatlantic wind-propelled transport system and to estimate the potential for mitigation through onboard energy storage technologies, together with other complementary strategies. To this end, a formulation is proposed based on the inventory required to guarantee a given service level, avoiding normality assumptions for travel-time distributions and using empirical percentiles derived from previous simulations.

In this context, the paper is organized as follows. Section 2 describes the reference conceptual vessel, the route analyzed, and the transit-time database used. Section 3 develops the logistics and financial model adopted to quantify pipeline inventory, cycle stock, and safety stock, together with their associated annual cost. Section 4 presents the results for the base case and discusses potential synergies with reversible propeller-turbines and energy storage systems. Finally, Section 5 summarizes the main conclusions and outlines future research directions.

2. Background and reference case

2.1. Conceptual vessel and propulsion configuration and Reference route and cargo

The reference case considered in this work is based on the conceptual vessel developed in Javier Sarmiento Gil's Master's thesis (TFM-377, ETSIN-UPM, 2025) [3], whose general arrangement is shown in Figure 1.

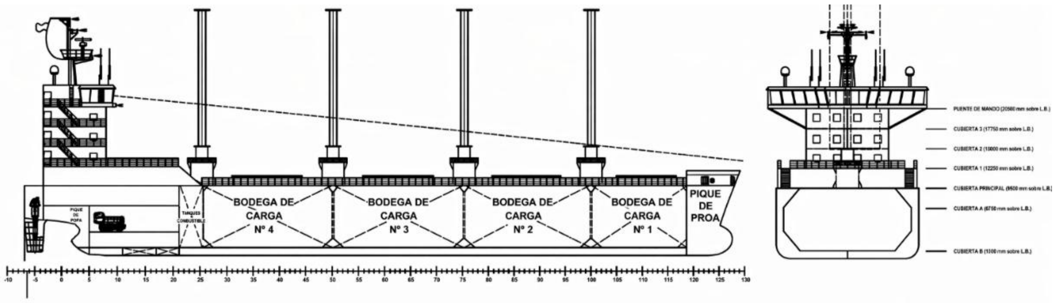

Figure. 1. *General arrangement of the fully wind-propelled conceptual vessel used as the reference case in the present study (TFM-377, ETSIN-UPM, 2025)* [3].

It is a Handysize bulk carrier of approximately 100 m length between perpendiculars, 20 m beam, 9.5 m maximum draft, and block coefficient Cb ≈ 0.69, conceived for dry bulk transport. The cargo capacity of 5,000 t is distributed among four main holds.

The distinguishing feature of the design lies in its fully wind-based propulsion system, implemented by four rigid symmetric-profile sails (NACA0015), approximately 20 m in height and with a total sail area of about 560 m². The system eliminates conventional main mechanical propulsion, so vessel speed depends exclusively on wind conditions and on the aero-hydrodynamic performance of the hull-sail system. The engine room mainly contains diesel-generator sets and other auxiliary services to ensure the proper operation of the vessel. This approach represents a conceptual break with wind-assisted propulsion systems (WAPS), in which wind energy supports a dominant mechanical propulsion system. Harbor entry and departure are assumed to be assisted by tugboats.

The reference case considered in this work is based on the conceptual vessel developed in Javier Sarmiento Gil's Master's thesis (TFM-377, ETSIN-UPM, 2025) [3], whose general arrangement is shown in Figure 1. The transport of thermal coal between Hampton Roads (USA) and Rotterdam (The Netherlands) was selected as the case study, as it is representative of transatlantic dry-bulk traffic. Coal was chosen on the basis of two criteria [3]:

- It is a non-perishable commodity with low intrinsic value and therefore less sensitive to variations in transit time.
- It makes it possible to analyze the economic impact of variability on inventory from the perspective of an industrial facility operating under lean-production principles.

2.2. Generation of the transit-time database

Travel times were obtained through [3]:

- Vessel polar diagrams relating speed to wind intensity and angle. These were generated using the ShipSIM library developed by Basilio Puente Varela and María Dolores Fernández [6].
- A weather-routing algorithm developed within the thesis itself.
- Historical MERRA-2 wind data with hourly resolution [7].

More than 8,000 simulations were carried out on the UPM Magerit 3 supercomputer [8] for each direction of the route, generating monthly distributions of travel duration. The result is a statistical database of transit times differentiated by month and sailing direction.

2.3. Transit-time distributions

Table 1 show the monthly distribution of transit times for the Hampton Roads → Rotterdam route (outbound) and for the return leg, respectively.

Table 1. *Monthly transit time statistics for the Hampton Roads – Rotterdam route.* μ_L*denotes the mean transit time and* L_{90}*the 90th percentile transit time calculated from simulations based on historical meteorological data.*

	Eastbbound (USA-NL): Go			**Westbound (NL-USA): Return**		
Month	L_{10} **(days)**	L_{90} **(days)**	μ_L **(days)**	L_{10} **(days)**	L_{90} **(days)**	μ_L **(days)**
January	25.4	30.3	27.8	30.4	36.5	33.9
February	24.0	31.0	27.5	28.9	34.5	31.8
March	24.5	35.8	28.6	30.5	38.8	33.0
April	26.9	39.5	34.0	36.5	47.0	41.9
May	36.5	44.1	40.8	42.1	49.4	45.4
June	31.6	43.0	37.0	35.6	50.7	42.2
July	30.5	38.5	34.6	47.4	54.7	50.8
August	30.9	46.4	38.8	39.3	47.4	43.5
September	30.0	42.7	36.3	33.5	42.1	37.4
October	29.9	38.4	34.6	31.4	44.7	35.3
November	23.4	30.8	26.9	35.8	42.7	39.2
December	24.2	30.6	27.4	33.1	39.6	36.6

On the eastbound route, a clearly defined seasonality is observed. Winter months exhibit mean travel times on the order of 26–28 days, with moderate dispersion and relatively compact distributions. In particular, November appears to be the most favorable month in terms of both mean duration and variability.

By contrast, spring and summer months show a significant increase in mean transit time, reaching values above 40 days in May, together with a wider P10–P90 interval. August stands out as one of the months with the highest relative dispersion, indicating greater operational uncertainty.

It is noteworthy that, in most months, the mean and median are close to one another, suggesting approximately symmetric distributions, although with seasonal differences in the extent of the upper tail.

On the westbound route, transit times are systematically longer and variability is generally more pronounced. Annual mean values exceed those of the outbound leg by several days, and the P10–P90 interval widens especially during the summer months.

Seasonality remains evident, but with greater sensitivity to adverse conditions, which translates into more extended upper tails in certain months. From the standpoint of logistics sizing, this difference between directions is especially relevant.

The data show that variability is not homogeneous throughout the year and that there are months in which the relative dispersion of transit time is significantly greater. Although the distributions do not exhibit extreme asymmetries, the behavior at the upper end (P90) varies appreciably between seasons.

Since the subsequent economic analysis is based on sizing the inventory required to guarantee a given service level, the statistics of interest are not limited to mean travel duration, but explicitly include the upper percentile of the monthly distribution.

3. Methods

The methodological objective of this study is to quantify the economic impact associated with transit-time variability in a fully wind-propelled maritime transport system and to estimate the potential value of its mitigation through onboard energy storage.

In industrial logistics systems with stable demand, transit time is not an economically neutral variable. An increase in transport duration implies that the capital invested in the goods remains immobilized for a longer period before generating productive value at destination. This immobilization entails an opportunity cost [9].

From the importer’s perspective, purchasing the goods under INCOTERM FOB (Free On Board) conditions implies that risk and responsibility for the cargo are transferred to the buyer when it is placed on board the vessel at the port of origin [10]. Under FOB, therefore:

- The seller fulfills its obligation when the goods are loaded on board the vessel designated by the buyer.
- From that moment on, the buyer assumes risk, financial costs, and responsibility for the goods.

Therefore, capital equivalent to the value of the cargo begins to incur an opportunity cost from the moment of loading, regardless of the fact that the goods cannot yet be used in the production process.

Opportunity cost represents the return that immobilized capital could have generated in an alternative investment of comparable risk. In this study, an annual cost of capital of 8% is adopted, representative of a moderate-risk European industrial company; this value may be interpreted as the weighted average cost of capital (WACC) [11].

From this perspective, holding inventory for a longer period is equivalent to foregoing the financial return that this capital could have generated in another productive activity.

Three main inventory components can be distinguished in the logistics system analyzed (see Figure 2):

1. Pipeline Inventory: Corresponds to the goods physically on board the vessel during the voyage between origin and destination. From the moment of loading under FOB conditions until unloading at destination, the capital associated with those goods remains immobilized without generating productive utility. Its magnitude depends directly on mean transit time [12].
2. Cycle Stock at destination: Once the goods have been unloaded, the industrial plant consumes the coal at an approximately constant rate. If supply is delivered in lots equivalent to a vessel’s cargo, inventory at destination fluctuates between a maximum value (immediately after unloading) and a minimum value (just before the next arrival) [13] .
3. Safety Stock: Safety stock is an additional inventory held to absorb deviations from expected transit time. Its function is to guarantee operational continuity in the face of delays above the mean. Unlike cycle stock, safety stock exists exclusively as a risk-management mechanism associated with temporal uncertainty [9]. From a financial perspective, whereas cycle stock is structural, safety stock is induced by variability. Therefore, reducing transit-time dispersion allows the required safety stock to be reduced and, hence, lowers immobilized capital.

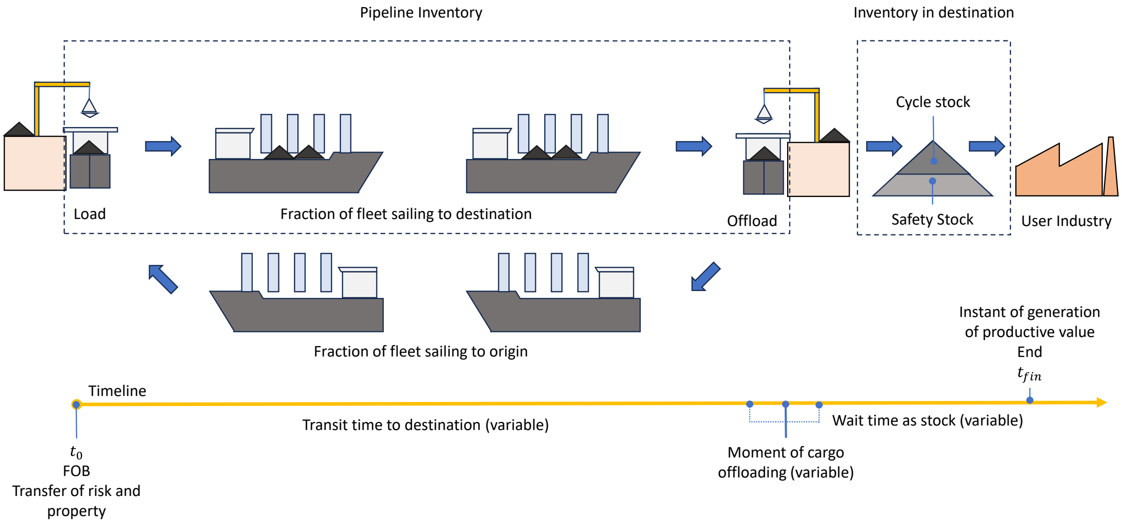

Figure. 2. *Conceptual scheme of the logistics flow under FOB conditions and the decomposition of the associated inventory. From loading on board at origin (transfer of ownership and risk to the importer), the cargo generates immobilized capital during maritime transit (pipeline inventory). After unloading at destination, inventory consists of cycle stock associated with the plant's constant consumption and safety stock maintained to absorb transit-time variability. Transport duration and its dispersion determine the total level of capital immobilized in the system.*

In industrial environments inspired by Lean principles, inventory is regarded as a form of waste insofar as it immobilizes capital and conceals system inefficiencies [14]. In the context of wind-propelled maritime transport, high transit-time variability forces higher levels of safety stock to be maintained in order to guarantee continuous supply [4]. This increase in inventory does not respond to productive needs, but to uncertainty in the logistics system. Therefore, improving operational reliability has not only technical implications but also financial ones, as it allows the capital immobilized in inventory to be reduced without compromising service level. The system analyzed here is modeled as a closed fleet of sailing bulk carriers making complete round voyages between the exporting and importing ports. In this context, transit variability affects not only the delivery lead time of each voyage, but also the overall replenishment cadence of the system, which strongly depends on the number of vessels in operation [15]. The analysis is structured in five stages:

1. Definition of the target annual transport volume.
2. Modeling of cycle time and fleet sizing.
3. Calculation of the inventory required to guarantee operational continuity and its associated annual cost.
4. Estimation of the cost of inventories.
5. Discuss the potential synergies with reversible propeller-turbines and energy storage systems to reduce these costs.

3.1. Definition of annual throughput and inventory sizing

The analysis starts from a target annual transport volume $Q_{year} = 139\,000 \text{ t/year}$, as assumed in the reference work [3]. Under the assumption of uniform consumption throughout the year, the equivalent daily demand is defined as

$$D = \frac{Q_{annual}}{365}, \quad (1)$$

Where D represents the average supply flow required by the consumer (t/day).

3.2. Modeling of cycle time and fleet size

From the wind-voyage simulations, the following statistics are available for each month m: Mean outbound transit time:$\mu_{outbound,m}$; Outbound 90th percentile:$L_{90,outbound,m}$; Mean return transit time:$\mu_{return,m}$; Return 90th percentile:$L_{90,outbound,m}$.

These statistics reflect the seasonality of the wind regime in the North Atlantic. A closed fleet composed of N sailing bulk carriers is considered, each with a fixed cargo capacity $Q_{voyage} = 5000 \text{ t}$ [3]. According to the adopted approach, the fleet is sized to satisfy the target annual volume Q_{annual} in terms of average annual capacity, not for the most unfavorable month. The management of seasonality and transit-time uncertainty is transferred to safety stock at destination.

Since a vessel that starts its outbound voyage in month m will complete its return in a later month, a deterministic month-to-month chaining scheme is adopted. As a conservative approximation, the return transit is associated with the following month (with a December–January circular adjustment). The mean round-voyage time for a vessel departing in month m is defined as:

$$\mu_{T,m} = \mu_{outbound,m} + \mu_{return,(m+1)} + t_{port}, \tag{2}$$

where t_{port} represents the total time associated with port operations (loading, unloading, and maneuvers). Conservatively, the 90th percentile of round-voyage time is approximated as:

$$T_{90,m} \approx L_{90,outbound,m} + L_{90,return,(m+1)} + t_{port}, \tag{3}$$

This approximation provides a prudent bound for the economic sensitivity analysis. The annual mean cycle time is obtained as:

$$\overline{\mu_T} = \frac{1}{12}\sum_{m=1}^{12} \mu_{T,m}, \tag{4}$$

The average number of round voyages per vessel per year is estimated as:

$$n_{RT} = \frac{365}{\overline{\mu_T}}, \tag{5}$$

If each vessel transports Q_{voyage} tons per voyage, the annual transport capacity per vessel is:

$$Q_{ship} = Q_{voyage} \cdot n_{RT}, \tag{6}$$

The minimum number of vessels required to satisfy the target annual volume is:

$$N = \left\lceil \frac{Q_{annual}}{Q_{ship}} \right\rceil, \tag{7}$$

This parameter is critical, since fleet size directly conditions the robustness of the system against temporal transit variability.

3.3. Inventory model

The inventory required by the importer is decomposed into (i) structural inventory in transit toward destination (pipeline inventory), (ii) operating inventory at destination associated with plant consumption and with the cadence at which vessels unload at the import port, and (iii) safety stock associated with the temporal variability of vessel unloading times [16]. Since transport is performed by a closed fleet of N vessels completing full round trips, pipeline inventory depends directly on the number of vessels and on the fraction of time they spend sailing loaded toward destination [17].

Each vessel completes, on average, one cycle every $\mu_{T,m}$ days. Therefore, the cadence at which loaded vessels arrive at the destination port is:

$$\lambda_m = \frac{\mu_{T,m}}{N} \left(\frac{\text{days}}{\text{ship}}\right), \tag{8}$$

If each voyage carries a fixed cargo $Q_{voyage} = 5000$ t/ship, the average flow supplied by the fleet is:

$$D_m = \frac{Q_{viaje}}{\lambda_m} \text{ (t/día)}; \tag{9}$$

The fraction of time that a vessel spends sailing on the outbound leg (loaded toward destination) during month m is expressed as:

$$f_{E,m} = \frac{\mu_{outbound,m}}{\mu_{T,m}}, \tag{10}$$

Therefore, the average number of vessels simultaneously in transit toward destination is:

$$N_{E,m} = N\, f_{E,m} = N\, \frac{\mu_{outbound,m}}{\mu_{T,m}}, \tag{11}$$

Under the assumption of full-load navigation, the average pipeline inventory toward destination is:

$$PI_{E,m} = N_{E,m}\, Q_{voyage}, \tag{12}$$

Safety stock is associated with the need to cover supply delays for a given service level $\alpha = 0{,}90$ [15]. Its deviation relative to the mean cycle is therefore defined as:

$$\Delta T_{90,m} = T_{90,m} - \mu_{T,m}, \tag{13}$$

Since the fleet is sized on the basis of average annual capacity, the months with the longest cycle duration generate a temporary supply deficit that must be absorbed through stock inventory SS at destination [15]. In a fleet with N vessels operating in rotation, the effective replenishment variability is reduced by the aggregation (pooling) effect [18]. As a first-order approximation, an equivalent replenishment delay is introduced:

$$\Delta L_m^{(N)} = \frac{\Delta T_{90,m}}{\sqrt{N}}, \tag{14}$$

and monthly safety stock is estimated as:

$$SS_m = D_m\, \Delta L_m^{(N)}, \tag{15}$$

This formulation makes explicit the sensitivity of safety stock to fleet size: the smaller N, the greater the impact of cycle variability on supply continuity.

The total monthly inventory considered for economic purposes is:

$$I_m = PI_{E,m} + CS_m + SS_m, \tag{16}$$

where CS_m is the plant's cycle stock, which is approximately half of the mass consumed by the plant during the replenishment cadence period $CS_m \approx D \cdot \lambda_m/2$ [13].

On an annual basis, inventory can be obtained as the average over the 12 months:

$$\bar{I} = \frac{1}{12}\sum_{m=1}^{12} I_m, \tag{17}$$

For physical silo sizing, the maximum value is taken. It is assumed that port operations and consumption allow each arrival to be absorbed without significant overlap of two consecutive deliveries; under this assumption, physical sizing at destination is governed by one reception lot Q_{voyage} plus the maximum annual safety stock:

$$I_{dest,max} \; = \; Q_{viaje} \; + \; \max_{m} (SS_m), \tag{18}$$

3.4. Economic cost associated with inventory

The economic cost associated with inventory is decomposed into:

1. Monthly financial cost of immobilized capital.
2. Monthly physical storage cost at the terminal (applied only to safety stock).

Let i be the annual cost-of-capital rate (WACC). The equivalent effective monthly rate is obtained as [19]:

$$i_{month} = (1 + i)^{1/12} - 1, \tag{19}$$

For each month m, given the characteristic total inventory , the monthly financial cost associated with immobilized capital is:

$$C_{fin,m} = I_m \, p \, i_{month}, \tag{20}$$

where p is the unit price of coal under FOB conditions (€/t).

This term represents the monthly opportunity cost of the capital committed to goods in transit and in storage.

The physical storage cost at the terminal is applied only to safety stock, since inventory in transit does not generate logistics costs at destination.

If c_{alm} is the annual storage cost per ton (€/t·year), its monthly equivalent is:

$$c_{alm,month} = \frac{c_{alm}}{12}, \tag{21}$$

Therefore, the monthly physical cost is:

$$C_{alm,m} = (CS_m + SS_m)\, c_{alm,month}, \tag{22}$$

The total monthly cost associated with inventory is:

$$C_{hold,m} = C_{fin,m} + C_{alm,m}, \tag{23}$$

and the equivalent annual cost is the sum over the twelve months:

$$C_{hold} \; = \; \sum_{m=1}^{12} C_{hold,m}, \tag{24}$$

This formulation makes it possible to capture explicitly the seasonality both of transit times and of the cadence induced by the fleet, while maintaining financial and dimensional consistency.

3.5. Reversible Hydrokinetic Turbine

A reversible hydrokinetic turbine was evaluated as an onboard energy-recovery device during favourable wind-propelled sailing conditions. The turbine drag was introduced as an additional resistance term added to the bare-hull resistance obtained from the Holtrop-Mennen method:

$$R_{tot}(v) = R_{hull}(v) + D_T(v), \tag{25}$$

where $R_{tot}(v)$ is the total resistance; $R_{hull}(v)$ is the hull resistance and $D_T(v)$ is the additional drag induced by the turbine.

The turbine drag was estimated as:

$$D_T = \frac{1}{2}\rho A v_A^2 C_T, \tag{26}$$

where ρ is the water density; v_A is the inflow velocity and C_T is the drag coefficient of the hydrokinetic turbine assume as 0.8.

The electrical power delivered to the batteries was calculated as:

$$\dot{W}_{elec} = \frac{1}{2}\rho A v_A^3 C_P \eta_{gen} \eta_{elec}, \tag{27}$$

where $\dot{W}_{elec}$ is the electrical power delivered to the batteries; C_P is the power coefficient of the hydrokinetic turbine taken as 0.4; η_{gen} is the generator efficiency, assume as 0.95 and η_{elec} is the electrical conversion efficiency assume as 0.95.

The inflow velocity at the turbine was corrected using the wake fraction:

$$v_A = v(1-w), \tag{28}$$

where w is the wake fraction.

The speed reduction was obtained by imposing constant available effective propulsive power. For each initial sailing speed v_0, the reduced speed v_{new} was found from:

$$[R_{hull}(v_{new}) + D_T(v_{new})]v_{new} = R_{hull}(v_0)v_0, \tag{29}$$

In the spreadsheet, this was approximated using the cubic scaling of resistance power at low Froude numbers:

$$v_{new} = v_0 \left(\frac{W_E}{W_{E,new}}\right)^{1/3}, \tag{30}$$

where $\dot{W}_E$ is the effective power required to tow or propel the vessel at a given speed and $\dot{W}_{E,new}$ is the effective power that would be required to keep the original speed when the turbine is deployed.

$\dot{W}_{E,new}$ is calculated as:

$$\dot{W}_{E,new} = (R_{hull}+D_T)v_0, \tag{31}$$

3.6. Initial assumptions

The model developed in the previous sections requires the definition of a set of operating and economic parameters characterizing the logistics system analyzed. These parameters are taken as constant within each scenario evaluated and constitute the study's initial assumptions.

Table 2. *Initial parameters and assumptions of the model.*

Parameter (units)	Symbol	Value	Comment
Target annual mass flow (t/year)	Q_{annual}	139 000	Base case from the reference Master's thesis
Cargo capacity per voyage (t)	Q_{voyage}	5 000	Sailing vessel from the thesis, full-load navigation
Port time per cycle (days)	t_{port}	4	Loading + unloading + maneuvers (assumption)
Monthly mean outbound transit time (days)	$\mu_{outbound,m}$	[date]	From Table 1
Monthly outbound P90 transit time (days)	$L_{90,outbound,m}$	[date]	From Table 1
Monthly mean return transit time (days)	$\mu_{return,m}$	[date]	From Table 1
Monthly return P90 transit time (days)	$L_{90,return,m}$	[date]	From Table 1
Service level (–)	α	0,90	In 1/10 cases transit is slower
FOB coal price (€/t)	p	90	Acquisition value (FOB) [20]
Annual cost of capital (–)	i	8%	Importer's WACC (annual rate) [11]
Physical storage cost (€/t·year)	c_{alm}	10	Estimated from [21]

4. Results and discussion

Figure 3 shows the monthly evolution of mean round-voyage time and its 90th percentile, together with the effective replenishment cadence at destination associated with a fleet of six vessels. A marked seasonality is observed, with maximum mean duration and dispersion during the spring–summer months and minima in winter. This temporal variability translates directly into a non-uniform cadence at the importing port, since the frequency of vessel arrivals depends on monthly cycle time.

In the months with the longest transit times, the cadence decreases (a larger number of days between arrivals), which increases the inventory requirement at destination. By contrast, in months with shorter cycles, supply frequency increases. Thus, even with a fixed number of vessels (N = 6), the fleet generates an intrinsically variable supply pattern, which is one of the determining factors in sizing both cycle stock and safety stock.

Figure 4 represents the monthly effective deviation of round-voyage time corresponding to the 90th percentile relative to the mean value, once corrected for the aggregation (pooling) effect of a fleet of six vessels. It can be observed that, even when the individual dispersion of transit times reaches significant values in certain months (especially during the summer period), the simultaneous operation of several vessels substantially attenuates the effective variability perceived by the logistics system.

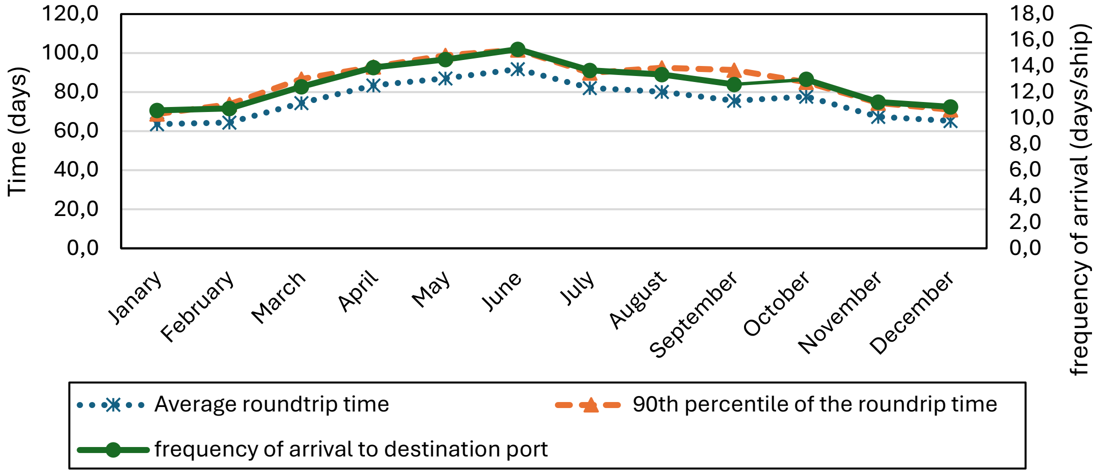

Figure. 3. *Monthly evolution of mean round-voyage time and its 90th percentile, together with the effective cadence of supply at destination for a fleet of six vessels. Transit-time seasonality translates into a variable arrival frequency at the importing port, conditioning the inventory required to guarantee operational continuity.*

From an operational standpoint, the pooling effect reduces the equivalent replenishment-time deviation, since the arrival of multiple vessels operating on staggered cycles smooths the supply cadence. Therefore, the effective deviation $\Delta L_m^{(N)}$ is markedly smaller than the raw deviation of individual transit time (Figure 4).

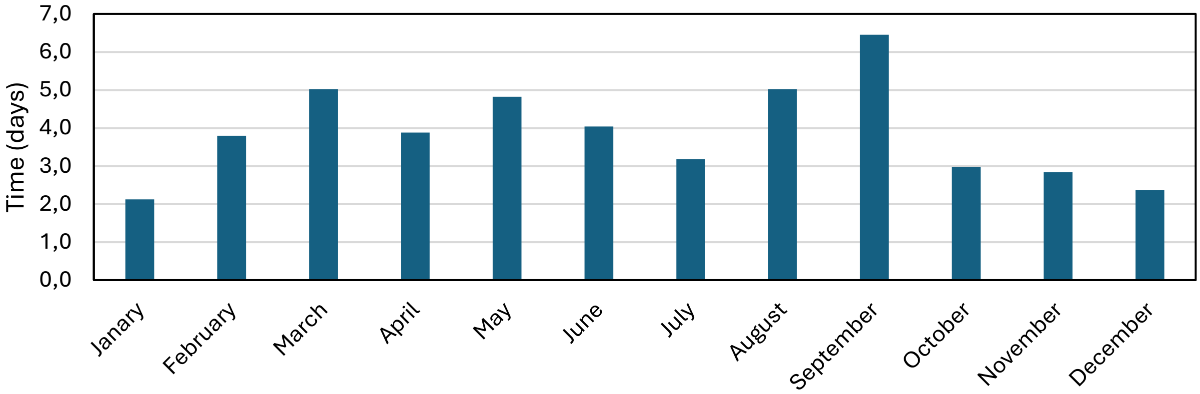

Figure. 4. *Monthly effective deviation of round-voyage time corresponding to the 90th percentile relative to mean round-voyage time, corrected by the aggregation (pooling) effect of a fleet of six vessels $\Delta L_m^{(N)}$ (see Eq. 14). The reduction induced by the simultaneous operation of several vessels attenuates individual transit variability, moderating the level of safety stock required at destination.*

The economic implications are relevant. Since safety stock is proportional to this effective deviation, the statistical smoothing associated with the fleet limits the level of additional inventory required to guarantee the adopted service level. As detailed below, this explains why, in the base case analyzed, the cost associated with safety stock represents a relatively small fraction of total inventory cost, the dominant component being structural pipeline inventory, which is linked to mean travel duration rather than to its dispersion.

This result qualifies the initial hypothesis according to which the main economic penalty of wind navigation would derive from its high variability. In the context of a moderately sized fleet (N = 6), the aggregation of sailing cycles significantly reduces the impact of such variability, shifting the economic focus toward mean transit duration.

Figure 5 shows the monthly breakdown of the total cost associated with coal inventory at destination, distinguishing among the financial component of pipeline inventory, the financial cost of cycle stock, the financial cost of safety stock, and physical storage costs.

The total annual inventory cost for the case study analyzed amounts to approximately €179,500, distributed unevenly throughout the year due to transit-time seasonality. The dominant component is the financial cost of pipeline inventory, directly linked to mean round-voyage duration. This result is consistent with the long duration of the transatlantic logistics cycle, which keeps a significant amount of capital immobilized for extended periods.

Second, the cost associated with cycle stock makes a relevant and relatively stable contribution, since it depends mainly on lot size (vessel capacity) and not on temporal variability.

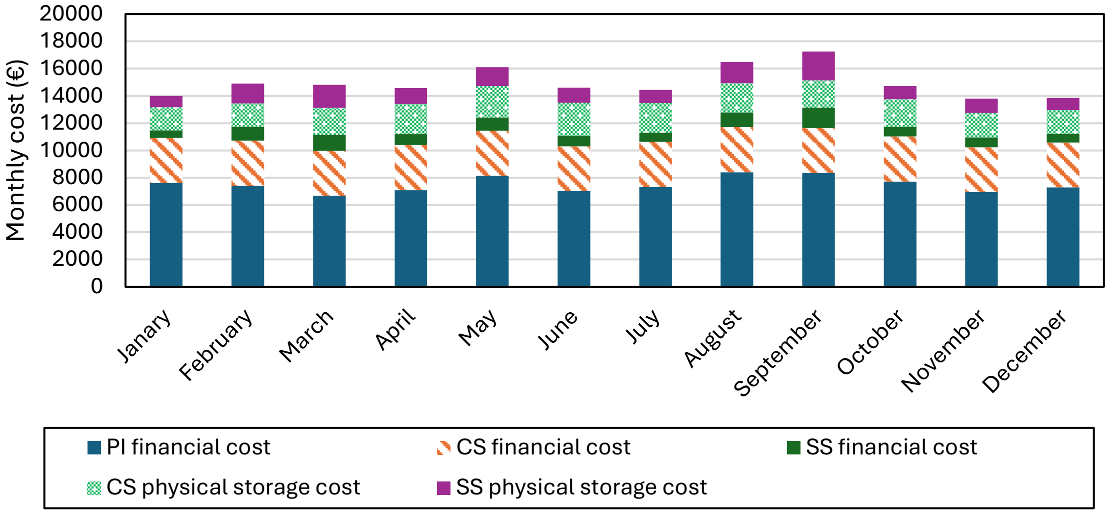

Figure. 5. *Monthly breakdown of the cost of coal inventory at destination for the case study considered. The financial components associated with pipeline inventory, cycle stock, and safety stock are represented, together with physical storage costs. The estimated total annual cost amounts to €179,500, dominated by the component associated with mean transit duration.*

By contrast, safety stock (SS) represents the smallest fraction of total cost, even in the months with the greatest effective excursion of transit time. This result confirms that, in a six-vessel fleet, the aggregation (pooling) effect attenuates effective variability and therefore limits the economic impact of temporal dispersion.

Finally, physical storage costs also make a significant contribution, depending on the volume actually stored at the terminal. The physical storage cost of cycle stock is more important than that of safety stock.

Overall, the results indicate that, for this traffic and fleet size, the dominant economic factor is not transit variability but the mean duration of the logistics cycle.

Overall, the total annual inventory cost expressed per ton transported amounts to €1.29/t, far below the coal acquisition price under FOB conditions. This result indicates that the economic penalty associated with longer and more variable transit times does not substantially alter the competitiveness of fully wind-propelled transport. Considering that the reference thesis estimated a freight rate at least 10% lower for the sailing alternative than for the conventional one under current conditions, it may be anticipated that, from the perspective of a European industry oriented toward Lean principles, purely wind-based propulsion would retain a net economic advantage [3].

From a physical and operational perspective, wind-only propulsion leads to highly variable instantaneous speeds within each roundtrip, including prolonged low-speed or near-stillness conditions with prolonged periods of high-speed sailing. Given the nonlinear relationship between resistance and speed, this opens the possibility of a dual energy strategy in which excess propulsive power in favorable wind conditions is partially recovered and stored, and later used to sustain propulsion during low-wind periods. In principle, such systems could reduce both travel-time dispersion and, potentially, mean transit time. However, their effectiveness depends critically on system efficiency, hydrodynamic penalties, control strategies, and the temporal availability of suitable operating conditions.

For a turbine diameter of 2.5 m, $C_T = 0.8$, $C_P = 0.4$, $w = 0.25$, and generator electrical efficiencies of 0.95, the deployment of the turbine produced a moderate hydrodynamic penalty as shown in Table 3. Over the speed range from 0.514 to 2.086 m/s (1 to 6 kn), the predicted speed reduction remained between 0.032 and 0.231 m/s (0.06 kn and 0.45 kn), corresponding to approximately 6.2–7.5% of the original vessel speed. The estimated generated electrical power at 3.086 m/s at these conditions equals 11.3 kW, whereas increasing 0.514 m/s (1 kn) of speed from stillness would consume about 9.2 kW in propeller mode.

The results presented in Table 3 illustrate the potential kinematic interest of a reversible propeller–turbine system. At a vessel speed of 6 kn, the turbine mode is capable of generating approximately 8.8 kW of electrical power while penalizing the vessel speed by only 0.476 kn. This electrical power is of the same order of magnitude as the additional propulsive power required to increase the vessel speed from nearly zero to 1 kn, estimated at approximately 9.2 kW. Under a simplified first-order approximation, one hour of operation in turbine mode at 6 kn would therefore provide enough stored energy to propel the vessel for approximately 0.96 h at 1 kn during calm conditions. During the generation phase, the vessel would lose approximately 0.48 nautical miles due to the temporary speed reduction, but would subsequently recover approximately 0.96 nautical miles during a low-wind episode in which the vessel would otherwise experience near-zero speed. This simplified kinematic balance example suggests that transferring energy from high-speed sailing periods towards low-speed or calm episodes could potentially reduce both the mean transit time and its dispersion. These estimations should be interpreted as a preliminary conceptual approximation.

The benefit of this strategy becomes clearer during subsequent low-wind or calm periods. At low vessel speeds the instantaneous power generated by the turbine is small, due to the cubic dependence on inflow velocity. However, energy stored during previous higher-speed sailing periods can be used later to supply auxiliary loads or provide limited electric propulsion support. In this way, the turbine-battery system acts as a temporal energy-shifting device: it accepts a moderate speed penalty during favorable sailing conditions in exchange for improved operational capability when wind propulsion is insufficient.

Table 3. *Estimated propulsive power requirements and reversible propeller–turbine performance for different vessel speeds. The table compares the additional propulsive power required to increase vessel speed by 1 kn (0.514 m/s) with the electrical power that could be generated in turbine mode under a small speed penalty.*

Propeller Mode			Turbine Mode		
v (m/s) [(kn)]	R_{hull} (W)	W_{add1kn} (W)	Speed penalty (m/s) [(kn)]	Speed penalty (%)	W_{elec} (W)
0.514 [1]	5830	9201	0.004 [0.009]	0.87	51
1.029 [2]	21284	24392	0.019 [0.037]	1.86	394
1.543 [3]	43314	34770	0.046 [0.090]	3.01	1285
2.058 [4]	68869	40333	0.090 [0.175]	4.36	2920
2.572 [5]	94898	41081	0.154 [0.299]	5.97	5419
3.086 [6]	118351	37016	0.245 [0.476]	7.93	8792

This supports the integration of onboard battery storage not primarily as a continuous propulsion source, but as a buffer that increases the operational robustness of the wind-propelled vessel. This is consistent with the POSEIDON concept, where reversible hydrokinetic generation and onboard storage are investigated as a way to reduce transit-time dispersion and improve predictability in periods of weak wind.

5. Conclusions

The objective of this study was to quantify the economic impact associated with transit-time variability in a fully wind-propelled maritime transport system and to estimate the potential value of its mitigation through onboard energy storage technologies within the framework of the POSEIDON project.

Based on the transit-time database obtained from historical meteorological simulations and on a logistics-financial model built on empirical percentiles, the structural pipeline inventory, cycle stock, and safety stock required to guarantee continuity of supply in an industrial facility under FOB conditions were evaluated.

For the base case considered—a closed fleet of six Handysize vessels with a capacity of 5,000 t per voyage and a target annual volume of 139,000 t—the total annual inventory-related cost amounts to approximately €179,500. The dominant component corresponds to the financial cost of pipeline inventory, directly linked to the mean duration of the transatlantic logistics cycle. By contrast, safety stock accounts for a small fraction of total cost due to the statistical aggregation (pooling) effect resulting from the simultaneous operation of several vessels.

The results indicate that, for the coal traffic analyzed and for a moderate fleet size, the dominant economic variable is not travel-time dispersion, but its structural mean value. Preliminary results suggest that a reversible propeller-turbine in combination with energy storage systems can reduce both average transit times and transit time variability.

The following future research lines are identified: (i) integral optimization of the sail system, (ii) coupled energy modeling of reversible hydrokinetic systems and onboard storage, (iii) joint analysis of optimal vessel and fleet size, and (iv) extension of the model to trades with higher unit value or greater contractual sensitivity to delay.

This work shows that the economic assessment of fully wind-based propulsion should explicitly consider not only vessel operating costs but also the capital immobilized in the logistics chain, thereby providing a quantitative framework for assessing the real impact of reliability-enhancing technologies in sail-powered maritime transport.

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