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A System Dynamics Approach to Maritime GHG Emission Reduction: A Case Study on Turkish Bulk Carriers

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Abstract

The shipping industry is under increasing pressure to decarbonize. This pressure, driven by global regulations and the need to mitigate the effects of climate change, provides the impetus for the current study to adopt a system-dynamics approach. The effectiveness of various strategies in lessening greenhouse gas emission within the context of Turkish Bulk Carriers. The model was experimentally calibrated using true ship data from Turkish-flagged bulk carriers that assisted in model development. The model accounts for interactions among regulator-driven factors (Energy Efficiency Existing Ship Index/Carbon Intensity Indicator and carbon pricing), operational approaches (speed and efficiency), fuel prices, dissemination of new technologies, capacity constraints, feedback rules, and delays. Four policy scenarios, simulated through 2050, are: Business-as-Usual (BAU), International Maritime Organization (IMO)-based, Aggressive, and Technological Breakthrough. Annual carbon flow, cumulative carbon dioxide emissions, and changes in the composition of the world's shipping fleet (HFO/liquefied natural gas/Bio/Hydrogen) are included. Model calibration against independent statistics reveals negligible discrepancies between the model and historical data series for various parameters, and sensitivity analysis confirms vessel speed as the main elasticity factor, followed by conventional vessel share and average distance. The analysis provides evidence of an annual weakening of total carbon dioxide emissions in all studied pathways; however, substantial discrepancies remain regarding both timing and magnitude. Recommendations include that comprehensive measures, such as carbon pricing and operational and technological strategies supported by infrastructure investments, can reduce total carbon emissions and long-term costs. In contrast, reliance on isolated, applied technologies may increase cumulative emissions, even while delivering overall benefits.

Keywords: CO_2 emissions, alternative fuels transition, decarbonization, Turkish flagged vessels, system dynamic modeling

1. Introduction

The increasing global problem of climate change and other environmental issues has also placed substantial pressure on the marine community to reduce greenhouse gas (GHG) emissions. Global GHG emissions from international shipping were estimated at approximately 1,076 Mt in 2018. This represented almost 3% of global GHG emissions of CO_2 [1]. The Paris Agreement mandates that the global temperature increase be restricted to much below 2 °C, with aspirations to limit it to 1.5 °C [2]. In 2018, the International Maritime Organization's (IMO) Initial GHG Strategy targets a 40% reduction in carbon intensity by 2030 and a 70% reduction by 2050, supported by measures such as Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII), and Ship Energy Efficiency Management Plan (SEEMP) [3]. The strategy outlined immediate measures, such as the EEXI, CII, and improved SEEMP, to reduce short-term emissions. The revised strategy emphasizes the development of mid-term and long-term measures including the adoption of a global fuel standard and economic pricing system for shipping emission reductions that should be finalized by 2025 and implemented by 2027 while assuring that such process should include a fair and equitable transition [4]. These dynamic initiatives reflect the IMO's increasingly comprehensive approach by identifying and combining regulatory, technological, and economic measures. In such an environment, it is important

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to acknowledge the urgency surrounding fuel or technology changeovers (or both). Research on energy transitions has become increasingly prominent in recent work, with particular emphasis on alternative fuels, technologies, and regulations.

Research on alternative fuels and the energy transition has examined the mitigation potential and challenges of low- and zero-carbon fuels. Conventional fuels such as heavy fuel oil are being gradually replaced by low- and zero-carbon fuels such as liquefied natural gas (LNG), methanol, ammonia, hydrogen, and biofuels [5]. LNG and methanol are frequently seen as transitional options with short- to medium-term abatement potential; LNG has lower emissions that peak at the source, but this advantage is counterbalanced by methane slip during use; by contrast, the decarbonization value of methanol is heavily dependent on renewable production methods [6]. Hydrogen and ammonia are potential zero-carbon fuels for the future, but they present challenges, including low energy density, storage difficulties, high cost, and safety issues [7-9]. Biofuels are compatible with existing infrastructure and engines, providing near-term deployment benefits; however, the field-scale-up of biofuel production is limited not by the inherent feasibility of biofuels, but primarily by competing uses for feedstock, price fluctuations, and supply chain issues [10]. In parallel, technological and operational pathways have been identified as complementary decarbonization strategies. Each type of alternative energy has advantages and disadvantages; therefore, an integrated, systems-based approach appropriate to strategic decision-making is needed. At a systems level, the general consensus points to readiness of infrastructure, lifecycle emissions, and cost parity as ongoing key unknowns, while sector coupling and timely policy integration are more often seen as facilitators of sustainable energy transitions in the maritime sector [11-13].

System dynamics applications have emerged as significant analytical tools that effectively capture the interdependencies among technological diffusion, regulatory enforcement, and operational behavior. The need for a comprehensive perspective to understand the complex, multidimensional interdependencies among these actions also implies the use of system dynamics modelling. Current management research that relies on system dynamics modelling indicate that interventions involving regulatory and technology intervention as the “green” interventions offer the fastest emissions reductions in the maritime supply chains, for example LNG and slow steaming were also effective [14,15]. At the port level, modernization and operational optimization further contribute to mitigation efforts through system dynamics approaches, providing insights into the interdependent processes of emission reduction in port operations [16]. More recent research has confirmed the effectiveness of the system-dynamics approach for investigating carbon-mitigation processes in marine and coastal ecosystems that are driven by feedback mechanisms. These research efforts illustrate the complex interactions of economic, technical, and environmental factors in shaping carbon emission levels over time. Despite such advances, the system dynamics of various types of ships, particularly bulk carriers, remain inadequately assessed. This emphasizes the need for specialized system dynamics analyses that considers the particular characteristics and transition patterns of such an industry [17,18]. Nonetheless, alongside this overarching framework, the challenges pertinent to specific ship types must be assessed independently.

Bulk carriers, representing around 43% of the global fleet, constitute a distinct focal point for decarbonization research due to their disproportionately high fuel consumption, extended service lifespans, and key role in international freight supply [19-21]. The configuration of long-distance routes and the reliance on conventional heavy fuel oil, which result in increased GHGs and pollutant emissions, create notable disparities in the operational characteristics of boats compared with other vessel types [22,23]. Operational techniques such as slow steaming, maximum speed optimization, ballast water exchange, trim adjustments, and hull enhancements affect vessel energy efficiency in various ways and contribute to the EEXI and the CII [24,25]. Moreover, the number of studies on bulk carriers that are specific to ship type is limited. The majority of research evaluating fleets is compiled across several ship categories. Several studies using system dynamics consider dynamics specific to vessel type; however, understanding how the interconnections among regulatory, technological, and operational factors vary by vessel type remains limited. This gap is significant for research on ship types because it offers a more refined method to evaluate adherence to international and national regulatory standards and establishes a framework for assessing long-term investments and changes affecting shipowners and policymakers.

The energy transition becomes more straightforward from the point of view of the inconsistencies in the implementation of regulations and the varying degree of their application worldwide is when one analyses the flags of the ships. Several studies have examined global fleets. A flag-based analysis helps clarify a country’s obligations and assists policymakers and ship owners in making sound decisions and formulating effective strategies to achieve a rapid and efficient national-level energy transition. The average age of the Turkish-flagged bulk carrier fleet is around 15.8 years, whereas the average age of Turkish-flagged merchant vessels is 22.2 years. This indicates that there is a considerable reliance on traditional fuels, a slow transition to new technologies, and some limitations set by regulations [26]. The Turkish-flagged bulk carrier fleet plays an important role in trade between Türkiye and other countries. It also represents an important step in Türkiye's development as a maritime trading nation in the Black Sea, the Mediterranean, and globally [27,28]. Turkish-flagged bulk carriers are particularly vulnerable to emerging regulatory pressures under the IMO's decarbonization strategy and EU-related market-based measures, including the EU Emissions Trading System and a potential regional Emission Control Area [29]. Previous studies tend to isolate individual interventions—such as operational measures, LNG adoption, and port-level optimization—without integrating the complex feedback mechanisms among fuel transition, carbon taxation, and fleet renewal dynamics [26,30,31]. This study addresses a gap in the existing literature by offering a holistic framework for analyzing transitions among alternative fuels for the Turkish-flagged bulk carrier fleet. The study seeks to fill a gap in the literature because energy transitions for fleets of ships have not been examined in a system dynamics context. This study aims to contribute to the literature and to practice by providing a dynamic analysis of decarbonization in Turkey's bulk-carrier industry. Moreover, it serves as a methodological basis for studying ship decarbonization within a micro-level framework that needs to be analyzed in a macro-level context.

The system dynamics modelling method used in this study appears in the methodological framework section, which follows the introduction. The following section presents a detailed, step-by-step process for building the model while explaining the theoretical assumptions, causal loop diagrams, and simulation methods. The discussion and conclusion chapters present the key results from the model analysis and examine their policy and operational implications, providing evidence-based recommendations. The last section presents future recommendations and components of the model.

2. System Dynamic Modelling

System dynamics, pioneered by Forrester [32] (1961) and Sterman [33] (2000), enables the analysis of feedback-driven and time-delayed processes and has been widely applied in energy and environmental policy, including maritime decarbonization. Figure 1 illustrates that system-dynamical modelling process.

A working hypothesis is then developed to explain the observed behaviors using causal loop diagrams. The next phase requires scientists to build their models using evidence-based data that link stock-and-flow systems to mathematical equations. The model undergoes verification and calibration stages, comparing simulation results (outputs) with data from the field to determine its robustness. The model serves as a tool for policy analysis that allows users to test multiple scenarios, project future outcomes, and formulate suitable responses [34].

2.1. Problem Definition

The study's objectives are to monitor variations in emissions over time for bulk carriers flying the Turkish flag and to project future emission trends for these vessels. Emissions evolve as a result of the interplay among operational procedures, the rate of fleet modernization, technological advancements, and policy implementation. Various regulatory regimes, such as the Energy Efficiency Design Index (EEDI), SEEMP, and CII, along with carbon tax policies, seek to change fleet operations, but their effectiveness depends on how shipowners coordinate operational, compliance, and investment costs. The paper argues that different treatment approaches have detrimental effects, such as late transitions, rebound effects, and inconsistent compliance, due to the absence of a systemic perspective. System dynamics modelling employs several approaches; Vensim is a notable example. The ability to validate the model using sensitivity analysis and optimization enhances trust in the model and ensures transparent and reproducible outcomes, which enables Vensim to serve as

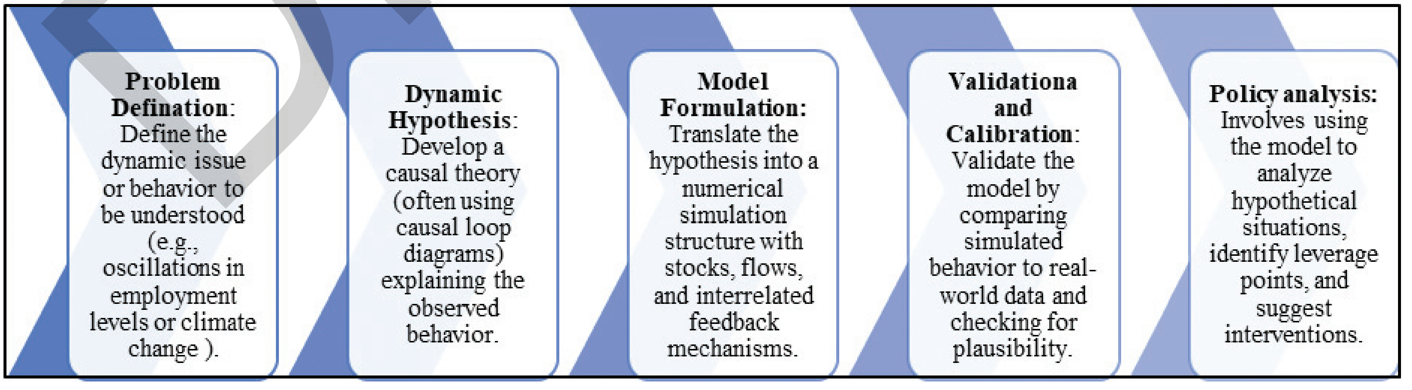

Figure 1. *System dynamical modelling process (Sterman, 2000) [38]*

a powerful decision-support tool for policy development and research in the academic community [35]. Unlike optimization or econometric methods, which perform well in static or component-level dynamic analyses, a system dynamics approach provides a comprehensive framework for analyzing dynamic interactions among factors such as technology, operations, and policy. The SD approach thus correctly formulates the non-linear, qualitative behaviors of a maritime decarbonization system that are not properly captured by linear and equilibrium models, such as life cycle assessment and input-output analysis. SD analysis was thus found to be the most suitable technique for analyzing long-term impacts of either policy changes or the adoption of new technologies in a Turkish-flagged bulk carrier shipping system.

2.2. Dynamic Hypothesis and Casual Loop Diagram

This study's dynamic hypothesis posits that the emission pathways of Turkish-flagged bulk carriers are determined by reinforcing and balancing feedback loops shaping fleet size, fuel switching, efficiency, and policy compliance. Investments in alternative fuels and technologies reduce emissions and accelerate adoption, while carbon taxes and compliance penalties increase costs and encourage fuel switching and efficiency improvements. Therefore, while strong regulations and well-designed economic instruments can accelerate the transition to low- and zero-carbon fuels, investment delays or policy gaps can lock the fleet into a high-emission pathway. Figure 2 illustrates the causal relationships and loop structure among these variables.

The causal-loop model demonstrates the complex relationships that influence the energy transition and the total carbon emissions of bulk carrier fleets. The vessel's composition (HFO, LNG, biofuel, and hydrogen vessels) has a closed-loop impact on total emissions, while regulatory compliance (EEDI, CII, SEEMP) and economic incentives prompt fleet behavior. The two systems operate through interconnected feedback loops that generate opposing effects, producing a self-sustaining cycle. The model presents a complete system-based view that shows how fleet changes, operational performance, and policy compliance lead to long-term changes in emissions.

2.3. Model Formulation

Figure 3 shows that the system dynamics stock and flow model incorporates key technological, operational, economic, and environmental variables to evaluate carbon reduction strategies for Turkish-flagged bulk carriers. These variables

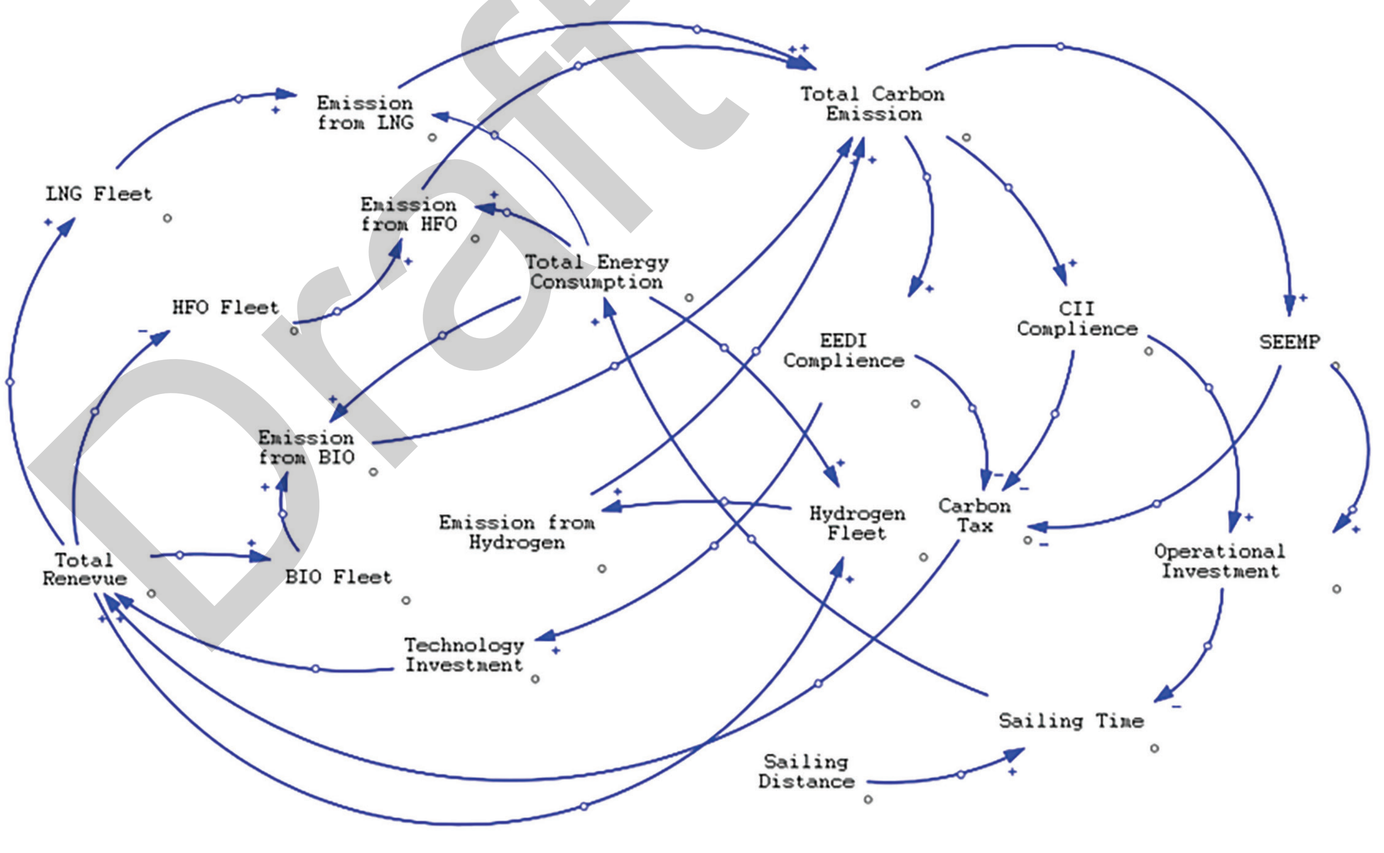

Figure 2. *Causal loop structure of the bulk carrier energy transition framework*

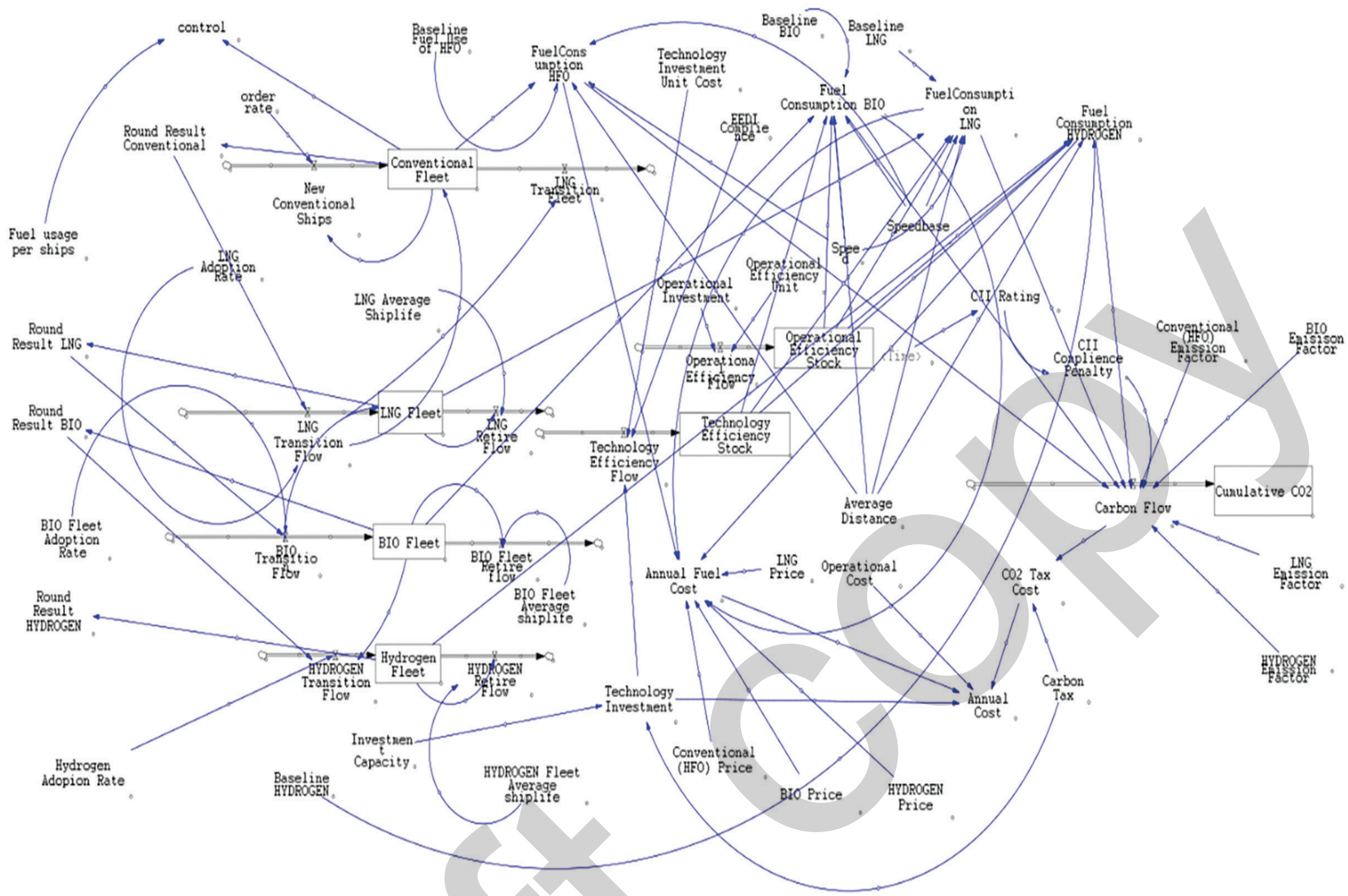

__Figure 3.__ Stock-flow diagram of energy transition the proposed model

act as fixed inputs, while the dynamic framework is driven by fuel consumption, carbon emissions, fleet transitions, retirements, and costs. The model links fleet size, average distance, baseline fuel use, and efficiency improvements to determine emissions across HFO, LNG, biofuel, and hydrogen ships. Structured as a stock–flow system with mathematical equations relating all variables, it comprises state variables, rate variables, auxiliary variables, and constants; detailed equations and abbreviations are provided in the Appendix Table 1.

2.4. Model Validation and Sensivity Analysis

Model verification is a vital part of SD. According to Table 1, the total carbon emissions of Turkish-flagged bulk carriers for 2020, 2021, and 2022 are presented. National-flag bulk carriers' emission data are not available from national sources. The total bulk carriers' emissions were obtained from the Organization for Economic Cooperation and Development (OECD) database. The Turkish Shipowners' Association, a respected, industry-specific organization, released the "2023 Outlook Report," which contained the ratio of Turkish-flagged bulk carriers to total bulk carriers worldwide. When the model results were compared with actual OECD data, differences were minor: 0.5% in 2020, 0.3% in 2021, and 0.8% in 2022. The model is sufficiently accurate and reliable for evaluating emission trends and flag-based distribution in marine operations, as evidenced by error margins within allowable bounds for policy-oriented simulation models. For analytical and decision-making purposes, the small differences between the simulated and actual values confirm the model's robustness.

__Table 1.__ Model reliability test

Year	Model valid	Real data	Ratio
2020	1.416.480 ton/year	1.423.597	%0.5
2021	1.131.500 ton/year	1.135.388	%0.3
2022	1.068.000 ton/year	1.076.455	%0.8

We used the coefficient of determination (R^2), formulated in Equation (1), and the root mean square error (RMSE), presented in Equation (2), to evaluate the level of agreement between simulated and observed values. In the following equations;

Coefficient of determination (R^2)-the proportion of variance in the observed data explained by the model.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{1}$$

RMSE calculates the average magnitude of prediction errors.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{2}$$

To evaluate the reliability of the model results, the simulated results and observed data for the validation years (2020-2022) were compared using two widely used statistical indicators: the coefficient of determination (R^2) and the RMSE. The study demonstrated a strong correlation between model forecasts and observations. R^2 was 0.9980, indicating that 99.8% of the variability in observed CO_2 emissions is explained by the model. RMSE was 6,764 tons per annum, indicating a slight deviation between the expected and observed values. The findings show that the system dynamics model provides a highly reliable representation of CO_2 emission trends in Turkish-flagged ships. Accordingly, the model is considered robust for use in scenario-based analyses and policy evaluation studies regarding maritime decarbonization.

Table 2 shows that, to test the strength and reliability of the system dynamics model developed in this research, a sensitivity test was conducted on important input parameters that could significantly affect emission trajectories and cost results. The examination focused on three significant variables related to cumulative carbon emissions: conventional fleet, average distance, and ship speed. In each scenario, the baseline [Business-as-Usual (BAU)] values of these variables were systematically altered by -20%, -10%, +10%, and +20%, respectively, while keeping all other variables constant. Table 2 shows the sensitivity of system dynamics model.

Sensitivity analysis results for 2030-2050 indicate that emissions are most sensitive to ship speed, followed by conventional fleet share and average cruising distance. A 10% increase in speed raises emissions by approximately 33%, whereas a 10% decrease reduces emissions by approximately 27%; at the 20% limit, the relationship becomes strongly non-linear, with emissions increasing by 73% at high speeds and decreasing by 50% at low speeds. This confirms the cubic relationship between speed and fuel consumption. Average distance affects emissions linearly, while changes in conventional fleet share have more limited but asymmetric effects. From a policy perspective, slow steaming is the fastest

Table 2. *Sensitivity analysis*

CO_2 emissions						
Critical values	**Value**	**2030**	**2035**	**2040**	**2045**	**2050**
Ship speed BAU	12 knot	8.620.230	9.993.680	10.674.400	11.054.600	11.314.200
Ship speed (+20%)	9.5 knot	4.277.070	4.958.520	5.296.280	5.484.930	5.613.750
Ship speed (+10%)	10.8 knot	6.284.150	7.285.390	7.781.650	8.068.830	8.248.090
Ship speed (+10%)	13.2 knot	11.473.500	13.301.600	14.207.600	14.713.700	15.059.300
Ship speed (+20%)	14.4 knot	14.895.800	17.269.100	18.445.400	19.102.400	19.551.000
Average distance	15000 mil	8.620.230	9.993.680	10.674.400	11.054.600	11.314.200
Average distance (-20%)	12000 mil	6.896.180	7.994.940	8.539.530	8.843.710	9.051.400
Average distance (-10%)	13500 mil	7.758.210	8.994.310	9.606.980	9.949.170	10.182.800
Average distance (+10%)	16500	9.482.250	10.993.000	11.741.900	12.160.100	12.445.700
Average distance (+20%)	18000	10.344.300	11.992.400	12.809.300	13.265.600	13.577.100
Conventional fleet	(33)	8.620.230	9.993.680	10.674.400	11.054.600	11.314.200
Conventional fleet (-20%)	26.4	6.985.650	7.922.960	8.466.190	8.770.180	8.959.610
Conventional fleet (-10%)	29.7	7.835.210	9.109.830	9.743.630	10.079.800	10.289.400
Conventional fleet (+10%)	36.3	9.667.810	11.209.300	11.969.800	12.367.600	12.641.000
Conventional fleet (+20%)	39.6	10.698.900	12.385.900	13.196.000	13.595.000	13.846.100
BAU: Business-as-Usual						

and most effective method for reducing emissions; synergistic benefits emerge when route optimization and reducing the share of the conventional fleet are combined.

2.5. Policies Analysis

This investigation presents four hypothetical scenarios to evaluate the potential development of the energy transformation system and associated carbon-emission reductions for Turkish bulk carriers through 2050. The first baseline comprises 33 Turkish-flagged bulk carriers of 1,000 GRT or above, representing the traditional fleet; this fleet is considered the starting point for assessing fleet-level transition pathways [36]. The scenarios BAU, IMO-Based, aggressive, and technology breakthrough vary according to a number of key input variables, including carbon pricing, investment capacity, operational and technological efficiency improvements, fuel price assumptions, compliance with the EEDI, and average cruising speeds. By systematically changing these variables, the study constructs scenarios that represent regulatory, market-driven, and technology-focused futures, thus allowing evaluation of the scenarios' long-term consequences for cumulative CO_2 emissions and carbon flow, as well as for the fuel-transition process in the maritime sector. Table 3 shows the parameters of that type of scenario.

Scenario 1 BAU: Assumes continuation of current trends without additional regulations. The fleet remains heavily dependent on fossil fuels, efficiency gains are modest, and no carbon pricing is in place. Emissions are projected to rise to 50% above 2008 levels by 2050, moving the sector further away from Paris Agreement targets.

Scenario 2 IMO-Based Scenario: Aligned with the updated 2023 IMO GHG Strategy, targeting 20-30% reduction by 2030, 70-80% by 2040, and net zero by 2050. Global carbon pricing is introduced in 2027, boosting investment while the costs of alternative fuels decline. The average speed dropped from 12 to 10 knots, supported by improvements in EEDI Phase 3 and CII compliance.

Scenario 3 Aggressive Scenario: Goes beyond the IMO strategy, consistent with the 1.5 °C Paris Agreement pathway. The fuel sector experiences rapid investment growth due to a carbon price of 200 USD per ton of CO_2, leading to a swift transition from fossil fuels to alternative energy sources. The industry will use LNG as a transitional fuel, but hydrogen and ammonia will gain market share starting in 2030. The average speed decreases to 9 knots because of strict policies and financial backing that aim to achieve zero emissions.

Scenario 4 Technology Breakthrough Scenario: The system depends on rapid technological progress rather than policy changes. The combination of fuel cells, green hydrogen, and ammonia, together with digital optimization creates cost reductions that will drive hydrogen prices down from USD 1,100 to USD 900 per ton between 2030 and 2040. Carbon pricing remains at 200 USD/ton, with revenues directed to research and infrastructure. Smart routing, digital twins, AI optimization, and advanced ship designs significantly enhance efficiency, thereby achieving 95% compliance with EEDI. This scenario suggests the sector could approach net zero by 2040, driven by faster-than-expected diffusion of innovations.

3. Results and Analysis

This section delineates three primary categories of results obtained from the model simulations across various policy scenarios, emphasizing carbon flow, cumulative emissions, and fleet evolution.

Table 3. *Type of scenarios and parameters*

Variable	Scenario 1-BAU (Reference)	Scenario 2-IMO-based scenario	Scenario 3-aggressive scenario	Scenario 4-technology breakthrough scenario
Energy transition delay	2	3	0	0
Carbon tax ($/year)	0	100	200	300
Investment capacity ($/year)	100000	200000	100000	300000
Operational efficiency stock	400000	500000	400000	500000
Technology efficiency stock	500000	600000	500000	600000
HFO_Price ($/ton)	600	600	600	600
LNG_Price ($/ton)	600	600	450	450
BIO_Price ($/ton)	900	800	900	800
HYDROGEN_Price ($/ton)	1 100	900	1100	900
EEDI_Compliance	0.85	0.95	0.85	0.95
Speed (knot)	12	10	9	10
Speedbase (knot)	13	13	13	13

3.1. Carbon Flow Results under Different Scenarios

Carbon Flow from 2020 to 2050 for the four scenarios shown as Figure 4. In every case, emissions fall, but not monotonically. The BAU trajectory is highest throughout most of the horizon, reflecting modest endogenous decarbonization in the absence of policy. The IMO-based scenario delivers earlier and deeper reductions, consistent with compliance pressures, while the aggressive scenario is the deepest and quickest to abate, reaching a near-zero band around 2035, well ahead of the others. The technology breakthrough trajectory initially tracks BAU, reflecting adoption and diffusion lags, and then accelerates after 2030; however, it cannot match the early depth of the Aggressive case. After 2040, inter-scenario dispersion narrows, reflecting saturation of fuel switching and diminishing marginal gains from abatement. The small year-to-year oscillations plausibly reflect dynamic delays (e.g., higher-order lag structures), threshold- and penalty-based responses (e.g., CII compliance lookups), and discretization and rounding effects.

Overall, the results indicate that near-term mitigation is acutely sensitive to operational levers (e.g., speed optimization) and to explicit carbon pricing, while dependence on a technological breakthrough alone is unlikely to achieve near-term targets; long-run declines must be sustained by regulatory and economic signals.

Table 4 illustrates the carbon levels across several scenarios. Annual CO_2 emissions decrease over time, but the timing of decreases differs by scenario. BAU remains the most carbon-intensive trajectory, demonstrating the limits of relying on advances driven largely by intrinsic considerations in the absence of significant state action. The IMO-based approaches begin to yield earlier, consistently lower trajectories than the BAU trajectory, consistent with compliance-induced behavior change. The aggressive pathway results in the deepest and fastest reductions, even approaching zero by mid-century. Technological innovations typically start on paths defined by BAU, amid delays in diffusion and adoption, and only ramp up much later; however, the mid-horizon rebound suggests that technology

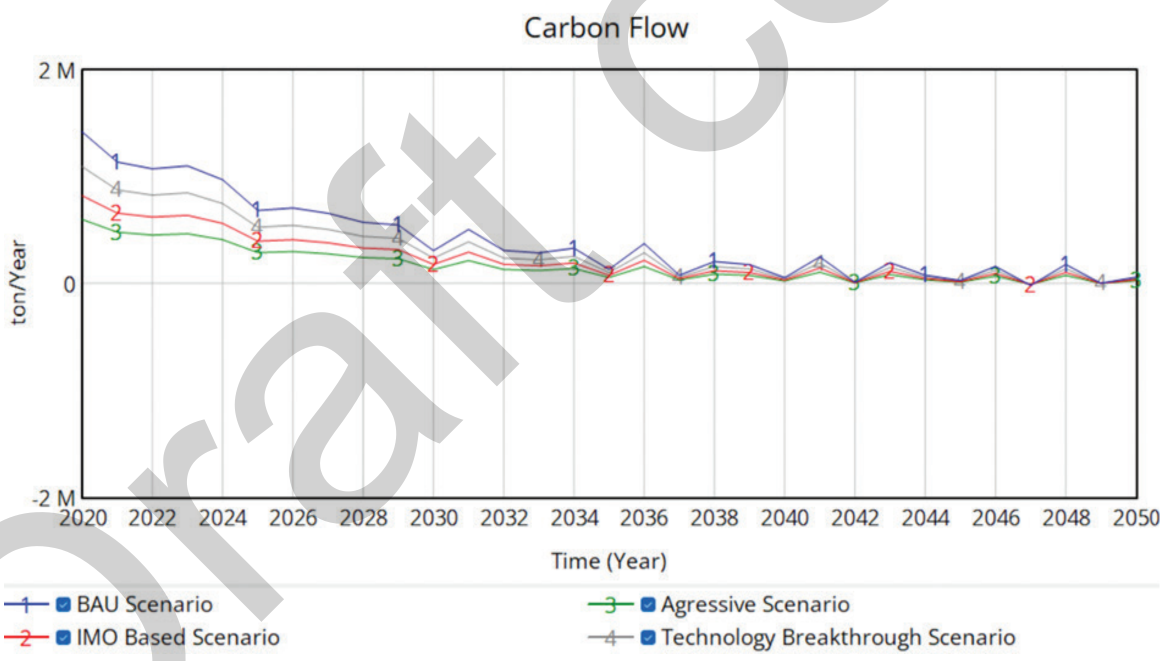

Figure 4. *Trajectories of carbon flow of Turkish-flag bulk carriers under four scenarios*

BAU: Business-as-Usual, IMO: International Maritime Organization

Table 4. *Carbon flow values between 2025-2050 years*

CO_2 emission (ton/year)					
Scenarios/years	2025	2030	2035	2040	2050
BAU-scenario	681.880	306.318	130.391	53.496	58.351
IMO-based scenario	394.607	177.267	75.457	30.958	33747
Aggressive scenario	287.668	129.228	55.008	22.568	2475
Technology breakthrough scenario	525.221	235.943	121.287	136.193	32.178

alone does not produce effortless or timely reductions without additional operational and policy frameworks. Ultimately, pathways become established toward the lower end when fuel switching saturates and fleet-renewal effects accrue, with remaining variation dependent on policy stringency. The key drivers of these paths are well understood within shipping systems. Operational techniques, particularly speed optimization, yield non-linear fuel savings, with significant early gains. As uptake of low- and zero-carbon alternatives increases, the effective emission factor decreases over time. Regulatory and price signals (including CII-linked penalties and the carbon price) influence operational and investment decisions in favor of cleaner alternatives, demonstrating the early advantages of policy-driven pathways.

3.2. Cumulative CO_2 Emissions Results under Different Scenarios

The small oscillations present in the data are consistent with stock-flow dynamics. Delays at multiple stages of adoption (e.g., higher-order delays) may produce temporary overshoot and undershoot; compliance functions that are built on thresholds or lookups will have stepwise responses; irregular decisions (e.g., delivering batches of retrofits) are often portrayed using rounding. Each of these mechanisms supports transitions in specific years. The interaction among these elements explains some brief rebounds, particularly when the adoption of the technology occurs too quickly following a delay, even when in compliance. First, immediate objectives are best achieved when operational mechanisms and clear price signals support technological trajectories. Secondly, sole reliance on innovations is precarious because of delays in diffusion and regulatory barriers. Lastly, maintaining long-term reductions necessitates robust governance and pricing to prevent rebound effects as transitions advance and reach saturation.

Figure 5 annual CO_2 emissions of Turkish-flag bulk carriers in four scenarios, 2025-2050.

Figure 5 shows cumulative CO_2 (the time integral of yearly emissions) along four trajectories. BAU shows the steepest initial slope and highest trajectory overall, reflecting a lack of endogenous decarbonization. The IMO-based policy reduces the slope earlier and more steadily than BAU, reflecting compliance-driven behavioral changes (CII penalties/thresholds) and modest operational changes. Aggressive policies flatten the curve quickly; its slope decreases most steeply, showing that the combination of speed optimization, strong price signals, and accelerated fuel switching lowers yearly emissions substantially early on, thus putting the system on a much lower cumulative trajectory. The technology breakthrough initially tracks BAU, reflecting adoption and diffusion lags, and then exhibits a reduction in slope as new technologies spread. However, the initial "carbon debt" keeps the cumulative trajectory above the policy-anchored scenarios even after the slope improves.

The small variations in curvature along all trajectories capture the cumulative impact of changes in annual emissions. Higher-order adoption delays in stock-flow analysis produce

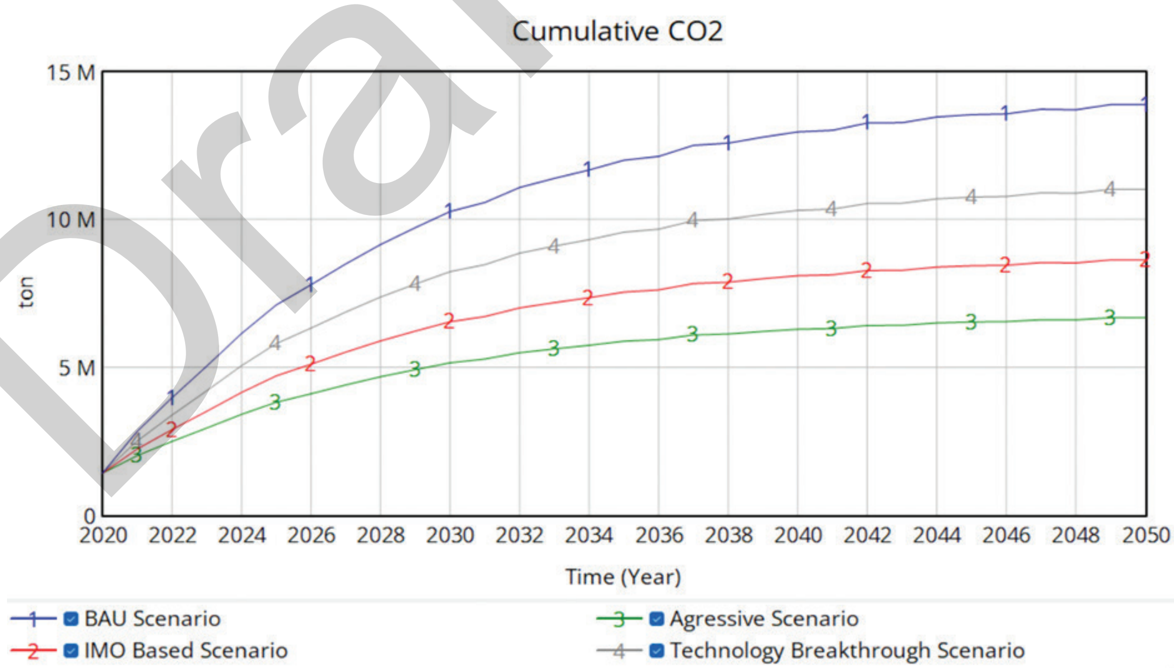

Figure 5. *Annual CO_2 emissions of Turkish-flag bulk carriers in four scenarios*

BAU: Business-as-Usual, IMO: International Maritime Organization temporary overshoots and undershoots in flows, manifested as small changes in slope. Threshold and lookup functions for CII compliance yield incremental responses as fleets shift between rating bands, and thus change the slopes. Irregular decisions, such as retrofit or delivery groupings, sometimes represented by rounding bundle transitions in specific years, briefly steepen or flatten the curve. In the technology breakthrough scenario, these mechanisms explain a mid-horizon inflection point: as breakthroughs begin to diffuse, the slope declines, but preceding BAU years keep the level high relative to policy-driven scenarios. Three implications follow. (i) Timing matters: early operational measures and explicit carbon pricing reduce the slope during periods when cumulative totals are most vulnerable, thereby preventing path-dependent "carbon debt". Technology is necessary but not sufficient; in the absence of concomitant policies and operational processes that mitigate diffusion lags, breakthrough pathways can produce higher cumulative emissions despite eventual progress. (iii) Ongoing governance is needed: as fuel switching saturates and marginal abatement declines, persistent regulatory and pricing signals help sustain low slopes and offset rebound effects associated with delays and thresholds.

Table 5 shows that cumulative CO_2 increases over time; therefore, the slope of each trajectory contains this information. The BAU case exhibits the highest increase, reflecting minimal endogenous decarbonization. The IMO-based case lowers the slope earlier and more continuously through compliance-induced behavioral change and moderate operational improvements, yet cumulative growth continues, suggesting that compliance alone is insufficient. The Aggressive pathway rapidly flattens through the implementation of speed optimization, robust carbon-price signals, and accelerated fuel switching, thereby locking the system into a fundamentally lower cumulative pathway.

In contrast, technology breakthrough initially follows BAU due to adoption and diffusion lags; however, as its pathway decreases after innovations become widespread, the resulting "carbon debt" maintains the cumulative total above that of policy-anchored scenarios. The years 2025-2030 represent the window of divergent trajectories; between 2030 and 2035, rapid fuel transitions and incremental responses occur as fleets cross CII thresholds; after 2035, the curves progressively flatten as fuel switching becomes saturated and marginal abatement diminishes. Minor fluctuations result from year-to-year flow changes caused by higher-order delay chains, threshold or lookup compliance regulations, and occasional judgments about refitting or delivering. The findings indicate that only policy packages that incorporate operational measures, continuous pricing signals, and vigorous deployment of technology effectively mitigate the slope during critical periods. In contrast, sole reliance on technology is insufficient. Because of diffusion lags, this can contribute to a higher cumulative load, even though it ultimately decreases. Ongoing governance is required to keep low slopes in check and prevent rebound effects.

3.3. Changes in Total Number of Ships and Annual Costs under Different Scenarios

The fleet's composition is expected to undergo substantial changes during the research period. As traditional ships diminish in prominence, vessels powered by alternative fuels are capturing an increasing share of the overall fleet. LNG and biofuel fleets exhibit early adoption, while hydrogen shows a significant rise in subsequent years. The subsequent section presents comprehensive trends for each fuel type.

Figure 6 shows the evolution of fleet composition (number of ships) by fuel under baseline assumptions, with a gradual phase-out of the conventional segment, an initial but ultimately short-lived adoption of LNG, a slow but steady ramp-up of biofuel-ready tonnage, and a lagged, stuttering expansion of hydrogen ships. The phase-out of traditional ships is consistent with age-related retirements and regulatory compliance demands for efficiency and intensity (e.g., EEXI/CII), which tighten operating parameters even without strong price signals. The early take-up of LNG reflects its readiness, retrofit potential, and regulatory acceptance as a bridge; however, its later plateau and decline are consistent with increasingly stringent well-to-wake standards, growing scrutiny of methane emissions, and prospective carbon pricing that undermines its medium-term advantages and increases lock-in risks. The use of biofuels increases gradually as drop-in blends leverage existing infrastructure; however, supply, certification, and

Table 5. *Total CO2 emissions values between 2025-2050 years*

Total CO_2 emission (ton)					
Scenarios/years	2025	2030	2035	2040	2050
BAU_Scenario	7.240.100	10.026.570	11.998.400	12.956.000	14.034.700
IMO-Based scenario	4.709.580	6.537.540	7.540.290	8.094.430	8.630.330
Aggressive scenario	3.817.150	5.149.750	5.880.740	6.284.710	6.657.380
Technology breakthrough scenario	5.754.950	8.232.550	9.576.270	10.304.800	11.018.100

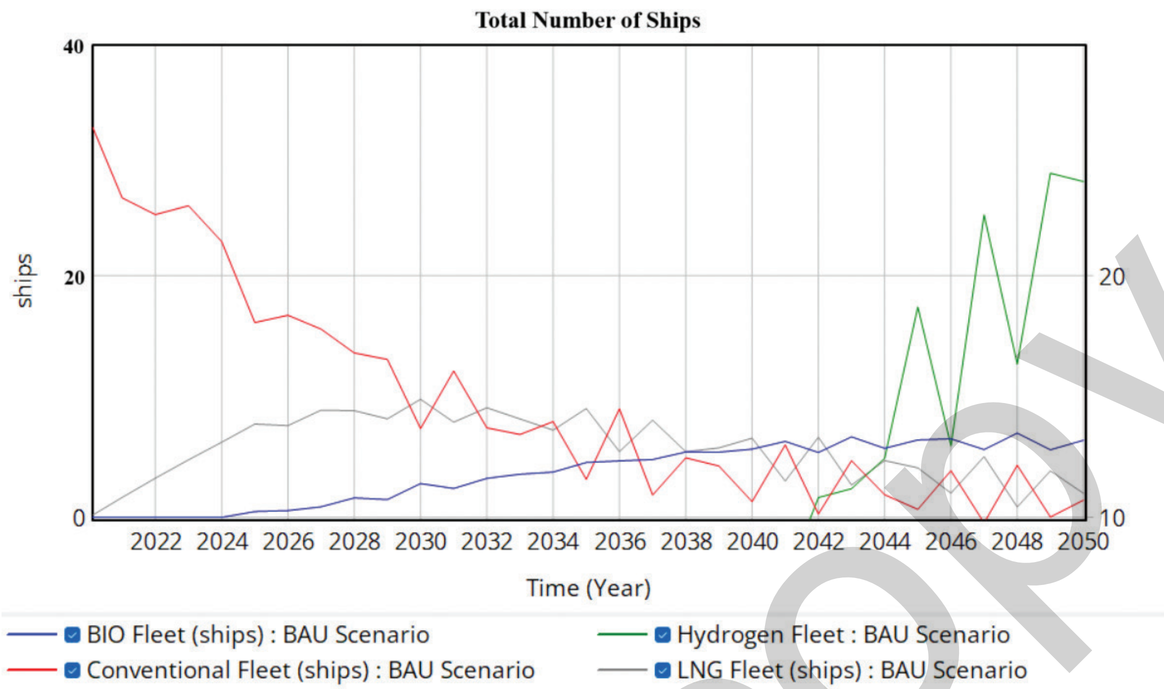

Figure 6. *Total number of fleet transition under BAU scenario*

BAU: Business-as-Usual

sustainability constraints limit scalability, reducing biofuels to an interim emissions-reduction measure rather than an ultimate solution. The emergence of hydrogen, gradual in some respects yet abrupt in others, is reinforced by the requirement for integrated infrastructure and by cost-related benchmarks. When green-corridor projects, bunkering investments, and financing arrangements (such as contracts for difference and tax incentives) are in alignment. Systemic newbuilding periods drive the annual changes described above. Within a stock-flow structure, the changes are legally permissible. A batch delivery system and retirements provide rapid additions; however, compliance reactions occur at a threshold that produces steps in the adoption profile, typically represented by higher-order delays. The implications for policy are obvious: the absence of high carbon prices, the failure of companies to make routine capital and operational investments in zero-emissions fuels, and the relaxation of intensity standards. The transitional period is characterized by delayed high hydrogen uptake and emissions. In contrast, through zero-carbon mechanisms, the zero-carbon transition will not be delayed. If we do not make substantial investments in liquefied natural gas and instead adopt short-term options, switching will be easier. Residual carbon-intensity performance, with substantial investment in ports and fuel infrastructure to offset the initial expenditure, will further reduce volatility.

Figure 7, translated from the energy transition framework, shows that the 2050 cross-section exhibits a distinct cost hierarchy: Aggressive is lowest, followed by IMO-based, then technology breakthrough, with BAU highest. This ranking is consistent with cost determinants incorporated into the model: annual fuel consumption, carbon pricing/CII penalty, and residual exposure to fossil fuel volatility. Concerted, early action in the Aggressive scenario (speed optimization, deep efficiency, and early fuel switching) reduces fuel demand and effectively bounds compliance and carbon costs by 2050, rendering the upfront capital outlay less burdensome than subsequent operating expenditure. IMO-based representation captures some aspects, but ultimately subjects the system to significant vulnerability due to lax regulatory stringency and a heterogeneous fuel mix. Technology-driven diffusion occurs late and involves high costs for zero-carbon fuel and infrastructure in 2050, including amortization of capital expenditures; it therefore costs more than policy-based measures, despite producing lower emissions. BAU remains the most costly due to ongoing high fuel consumption and the compounding of carbon and CII liabilities. Policy implication: Front-loaded, integrated decarbonization strategies reduce overall annual costs by mid-century; exclusive reliance on technology or postponed measures increases the cost baseline for 2050.

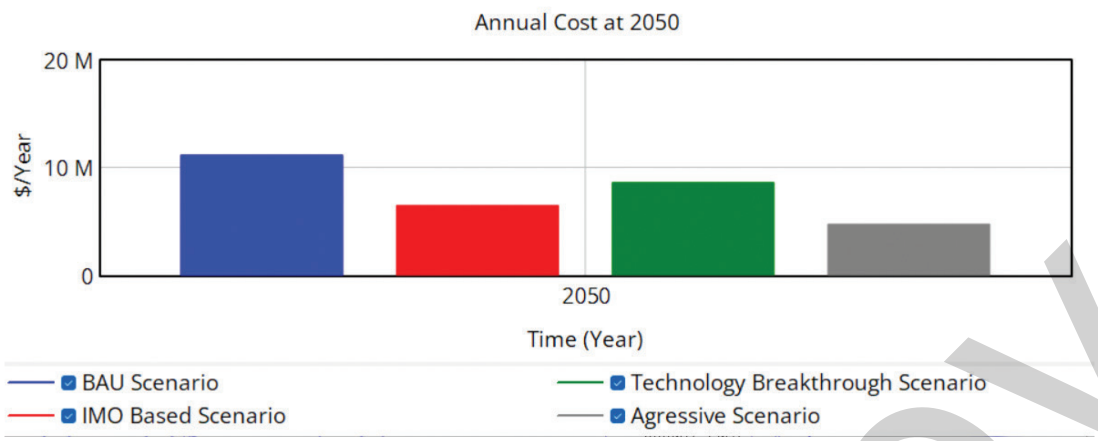

Figure 7. *Annual cost change at 2050*

BAU: Business-as-Usual, IMO: International Maritime Organization

4. Discussion

This study develops a flag-state-specific system dynamics model for fuel-type transformation in bulk carriers. It empirically parameterizes the model using ship-level data from Turkish-flagged bulk vessels and employs these inputs to analyze the co-evolution of regulatory stringency, operating practices, fuel prices, and technology adoption and their effects on emissions and fleet composition. Notwithstanding the constraints of irregular national data and the necessary assumptions of the scenario method regarding behavior and adoption, the model improves on the literature by making feedback mechanisms, multi-stage delays, threshold-compliance responses, and capacity limits (yards, bunkering) explicit within a national institutional context—a dimension largely absent from earlier work. Four policy-relevant scenarios frame the analysis: a BAU trajectory of weak price signals and investment constraints; an IMO-based trajectory that assumes progressive EEXI/CII tightening and moderate carbon-cost exposure; an aggressive trajectory featuring early carbon pricing, efficiency gains, and accelerated transition to zero-carbon fuels; and a Technology Breakthrough trajectory in which rapid post-2030 cost decline and corridor development drive uptake despite reduced early policy pressure.

The results demonstrate common decreasing patterns in annual emissions, with considerable variation in magnitude and timing. BAU is the highest emitter and produces the steepest cumulative trajectory; the IMO-based approach abates emissions sooner and more gradually due to compliance incentives, but it leaves significant residual emissions; the Aggressive strategy bridges the gap early by combining speed optimization, a willingness to send sustainable price signals, and early fuel switching. The evolution of technology generally leads to better outcomes; however, it also causes diffusion lags and delays due to the buildup of connectivity-related, costly infrastructure. Moreover, "carbon debt" maintains cumulative levels higher than they would be if changes in behavior were driven solely by policy incentives. The number of fleets reflects a systematic evolution in these trends: the fleet of conventional tonnage at the lower end of the contract range comprises progressively fewer ships. LNG ships are a bridging technology in the 2020s, but they level off as methane-slip and pricing deteriorate their advantage. Biofuel-ready ships are gradually being adopted as a near-term mitigation technology , but their deployment is still limited by sustainability and supply constraints. Hydrogen ships initially lag significantly, but once infrastructure and financial incentives are available, they rapidly increase in adoption, creating the possibility of "lumpy" year-to-year differences. We believe that the slight divergence in the trajectories is consistent with the effects of time delays, compliance thresholds, and batch changes or deliveries, rather than with noise in the expected models.

Technology is crucial, but it is ineffective without governance systems and pricing signals that minimize dissemination lag. These findings emphasize the need for Turkish maritime authorities to implement comprehensive flag-state initiatives aimed at reducing both yearly and cumulative rates.

5. Limitations and Future Research

This paper provides an experimentally validated system dynamics model of decarbonization for the Turkish-flagged carriers of bulk cargoes, subject to certain limitations. First, the model simplifies certain assumptions by treating them as constant over time, such as aggregate economic factors and average vessel lifespans, which in reality tend to change. Secondly, due to limited data found at the national level on specific details of a country's fleet structure and vessel-type fuel use patterns, some data had to be derived from global sources, which may include inferential components that introduce uncertainties. Thirdly, certain factors, such as human behavior (for example, investment choices of vessel operators beyond economic considerations), may differ from the assumptions these models make on average. Subsequent research may improve on these findings by incorporating human behaviors of actors (e.g., vessel operators) in addition to economic factors, into the design of port-level energy-infrastructure system models. In addition, economic mechanisms, such as carbon credit schemes, may be applied. Cross-country analysis of industry interactions in shipping-port sectors may improve the practical applicability of research findings.

6. Conclusion

This study developed a system dynamics model that was specifically designed for the flag states of bulk carriers that carry Turkish flags. The model featured options for transitional fuels to enhance operational efficiency and facilitate technology adoption in non-linear complex systems. The simulations indicate that one of the major factors that could positively alter emission trajectories is carbon pricing, together with increasing operational speed, improving efficiency, and switching to alternative fuels. These actions can lead to significant changes in emission trajectories compared with a BAU scenario. The research outcomes based on the IMO global greenhouse-gas strategy resulted in reductions of nearly 25% by mid-century. The fleet dynamics follow the global trends: traditional tonnage is kept by long-term contracts; LNG is a transitional fuel; sustainable bio-drop-ins can provide reductions quickly, within supply elasticities; and replacement zero-carbon fuels are expected after 2030, The time and character of the actions are very important in the integration of the cumulative effects; initiatives that are technology-driven face diffusion and delays because there is no infrastructure or it is lagging, thus resulting in a higher “carbon debt”.

Turkish-flagged vessels need to adopt an integrated approach to meet international goals cost-effectively. This means meeting escalating EEXI/CII requirements alongside ongoing carbon-pricing signals. Secondly, institutionalize operational measures (especially speed optimization) that include monitoring, reporting, and verification. Thirdly, accelerate the development of zero-carbon fuel infrastructure through public and private green corridors and financing (for example, contracts for difference and concessional capital), while managing LNG lock-in and using certified biofuels in the short term. Improved data systems and institutional coordination among maritime, energy, port, and shipyard stakeholders will enable adaptive adjustments and credible implementation. Taken together, these actions deliver prompt, cost-effective mitigation, enable a mid-term fuel transition, and guarantee long-term compliance for the Turkish-flagged bulk fleet.

Footnotes

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Authorship Contributions

Concept design: S. Uygur, and P. Bolat; Data Collection or Processing: S. Uygur, and P. Bolat; Analysis or Interpretation: S. Uygur, and P. Bolat; Literature Review: S. Uygur; Writing, Reviewing, and Editing: S. Uygur.

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Appendix Table 1. *System dynamic model mathematical equation table*

Variable Name	Description	Value	References
Baseline BIO fuel	Default biofuel consumption per unit distance	0.117	[37]
Baseline LNG fuel	Default LNG (liquefied natural gas) consumption per unit distance	0.949	[38]
Baseline H2 fuel	Default hydrogen consumption per unit distance	0.039	[39]
Baseline HFO	Default heavy fuel oil consumption per unit distance	0.11	[20]
Fuel usage per ships	Annual average fuel consumption per ship	1500	[40]
Speed base	Reference ship sailing speed	13	[38]
Speed	Adjusted/assumed sailing speed under a scenario	12	[41]
Investment capacity	Financial capacity of the fleet to invest in new technologies	100000	[30]
EEDI compliance	Compliance ratio with the Energy Efficiency Design Index (EEDI)	0.85	[3]
Operational investment	Total investment for operational improvements (retrofits, maintenance, efficiency measures)	1,500,000	[42]
Bio emission factor	CO_2 emission factor from biofuel combustion	0	[43]
Hydrogen emission factor	CO_2 emission factor from hydrogen use (close to zero)	0	[43]
LNG emission factor	CO_2 emission factor from LNG combustion	2,75	[1]
Conventional emission factor	CO_2 emission factor from conventional fuels (HFO/MDO)	3,15	[1]
Bio fleet average life	Average lifetime of biofuel-powered ships (years)	25	[40]
LNG average ship life	Average lifetime of LNG-powered ships	25	[40]
Hydrogen average ship life	Average lifetime of hydrogen-powered ships	25	[40]
Carbon tax	Tax applied per ton of CO_2 emitted	100	[44]
Operational cost	Annual or daily operational cost of ships	1,500,000 USD	[45]
Operational efficiency unit	A factor representing operational efficiency level	400000	[45]
Technology investment unit cost	Unit cost of adopting new technology (e.g., LNG retrofit, hydrogen fuel cell installation)	500000	[45]
LNG price	Unit price of LNG	600	[46]
Bio price	Unit price of biofuel	900	[39]
Hydrogen price	Unit price of hydrogen	1100	[44]
Conventional fuel price	Unit price of conventional fuels (HFO/MDO)	600	[46]
Average distance	Annual average distance travelled by ships (nautical miles)	15000	[40]
Fuel usage per ships	Annual average fuel consumption per ship	15000	[1]
Conventional fleet	Ships that operate using traditional fossil fuels	33	[36]

Appendix Table 1. *continued*

Variable Name	Description	Value	References
Fuel consumption H2	Base line H2* HydrogenFleet *AverageDistance*(1-0.3) / ((OperationalEfficencyStock/100)*(TechnologyEfficiencyStock/100))	Mathematical equation	
Fuel consumption Bio	Base lineBIO* BioFleet* AverageDistance*(1-0.2)* (Speed/ Speedbase)3/ ((OperationalEfficencyStock/100)*(TechnologyEfficiencyStock/100))		
Fuel consumption LNG	Baseline*LNGFleet*LNGAverageDistance*(0.01)*(Speed/ Speedbase)^3/ ((OperationalEfficencyStock /100)*(TechnologyEfficiencyStock /100))		
Fuel consumption HFO	AverageDistance*BaselineFuelUseHFO*ConventionalFleet* (Speed/Speedbase)^3*10		
Carbon flow	(bioemisisonfactor*FuelConsumption Bio+convemissionfactor* FuelConsumption HFO+ hydrogenemissionfactor\ *”FuelConsumption H2 |” + FuelConsumption LNG*lngemissionfactor)*(1+CII Complience Penalty)		
Rounded resulet CONV	INTEGER(ConventionalFleet)		
Rounded hydrogen	INTEGER(HydrogenFleet+1-0.0001)		
Rounded bio	INTEGER(BioFleet+1-1e-05)		
Rounded LNG	INTEGER(LNGFleet+1-1e-05)		
LNG transition fleet	LNG Transition Fleet*1		
Hydrogen transition flow	DELAY3(ROUNDEDRESBIO*HydrogenAdopionRate, 2)		
Bio transition flow	DELAY3(ROUNDEDRESLNG*BiofleetAdoptionRate, 2)		
LNG transition flow	DELAY3(ROUNDRESULTCONV*LNG AdoptionRate,3)		
Bio fleet retire flow	BioFleet/ Bio fleet Average Life		
Hydrogen retire flow	HydrogenFleet/HydrogenAVERAGEshiplife		
LNG retire flow	LNGFleet/LNG Average Ship Life		
Annual cost	Annualfuelcost+co2taxcost*Operationalcost+Technologyinvetment		
Technology invetsment	Investment Capacity*(0.5+0.001*carbontax)		
Operational efficiency flow	Operational investment/ Operationel efficiency Unit		
Technology efficiency flow	Technology Invetment*EEDI Complience/Technology Investment Unit Cost		
Control	ConventionalFleet*Fuel usage per ships		