

# System Dynamics Approach to Global Shipping Emissions

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**ABSTRACT:** This paper presents an improved System Dynamics (SD) model to assess the greenhouse gas (GHG) emission reduction measures between 2023 and 2050 at the container terminal of the Port of Koper. The new model builds on previous models and includes several subsystems that take into account many decarbonisation instruments such as the electrification of facilities, the introduction of alternative fuels (ammonia, methanol, hydrogen, biofuels) and onshore power supply (OPS). The simulation results show that emissions can be reduced by 88.6% by 2050, mainly through harbour equipment. The model follows the dynamics of the S-curve in the introduction and estimation of throughput growth in reality. Decarbonisation has not been fully completed but can be advanced with future technologies such as carbon capture for additional emission reductions. The study proves that dynamic modelling is efficient in long-term sustainability planning and provides a scalable model that can be used by other ports wishing to meet the IMO 2050 targets.

## 1 INTRODUCTION

Maritime shipping is a mainstay of the global economy and acts as a lifeline between global trade networks. Yet this ubiquitous activity generates enormous amounts of greenhouse gas emissions, accounting for around 3% of total global emissions. Growing concern about climate change has encouraged global action to reduce greenhouse gas emissions from all sources, including shipping. International bodies such as the International Maritime Organisation (IMO) are leading efforts to make the shipping industry carbon neutral by 2050 [1]. Greenhouse gas emissions are to be significantly reduced by 2030 and 2040, which is a necessary step on the way to complete decarbonization. Greenhouse gas emissions from the maritime sector come largely from the combustion of fossil fuels by ships (mainly HFO and LSFO), which release carbon dioxide, methane and nitrous oxide as well as sulphur and nitrogen oxides, which have an

impact on public health. While ports are also a source of these emissions, they are one of the main drivers of decarbonization, both by curbing emissions from ships in port and by spearheading the decarbonization of the various maritime actors.

Ports are part of the global supply chain and act as hubs between shipping and land transport. Due to rising energy prices and the need to reduce their overall emissions, ports are taking measures to reduce their energy needs, leading to stricter environmental measures to limit pollutants and greenhouse gas emissions from energy consumption [2]. The integration of new technologies into port operations brings many difficulties, such as problems with traffic congestion, harmonisation of surrounding residential areas with the port and the calculation and reduction of CO<sub>2</sub> emissions, as well as general energy transition planning [3]. Ports have far-reaching impacts that usually involve rail, road and inland waterway

networks, so it is important to consider the environmental issues associated with these interlinked modes of transport [4]. The sustainability of maritime transport consists of environmental, economic and social aspects, with the environment taking centre stage in terms of emissions from ships and port machinery [5]. Ports must not only decarbonise, but also combat the effects of climate change, such as rising sea levels and increasing storms. To effectively reduce port emissions, including emissions from docking ships, the contributions of different emission sources need to be assessed.

This quantification enables targeted policies and measures to reduce emissions [6]. Technological solutions such as exhaust gas cleaning systems and alternative fuels are at the centre of reducing air pollution and climate change from ships. However, a rigorous assessment of overall sustainability must be made when selecting measures to reduce air pollution. The same applies to ports. Maritime players are increasingly forced to change their business and strategies due to new, ever-changing environmental regulations and consumer pressure for sustainability. This type of transition generally means the introduction of multimodal transport chains, alternative fuels and the imposition of sustainability requirements on their partners [7].

## 2 LITERATURE REVIEW

Ports around the world are trying to find the most appropriate strategies for their decarbonization, from electrification to the introduction of alternative fuels and energy efficiency measures [8]. Not only are most port activities leading to decarbonization, but the sustainability of ports in general is also being driven by the inclusion of new green infrastructure [9].

Synergies and standardisation between environmental and energy management as part of the "Green Port" concept can improve the competitiveness of Mediterranean ports [10]. By standardising environmental improvement measures and working together, ports can reduce their greenhouse gas emissions more effectively and improve their overall sustainability performance. In this way, advanced technologies can be implemented and ports can be made more environmentally friendly by shifting from carbon-intensive to low-carbon operations [2]. This will involve the introduction of new fuels, renewable energy and new technologies. Recent studies indicate that incentives need to be created to accelerate the introduction of electromobility in river and maritime shipping and reduce ship emissions [11]. Collaboration between shipowners, terminal operators and policy makers is required for the effective introduction of new technologies [12]. Improving optimisation and further developing new technologies, including alternative fuels and renewable energies, are basic prerequisites for efficiently reducing emissions [13]. The integration of renewable energy such as solar and wind power could also be feasible in some ports.

Ports play a dual role in decarbonization, firstly by reducing their own emissions and secondly by promoting decarbonization in the maritime sector [14]. To reduce port emissions even further, alternative

fuels, renewable energy and other technologies should be explored to accelerate emission reductions [15]. For these solutions to materialise, infrastructure needs to be upgraded for the introduction of alternative fuels, which is currently not the case for the majority of measures [16]. The standardisation and high cost of infrastructure in ports and on ships for the widespread introduction of various measures could also become a challenge [17]. The appropriate introduction of alternative fuels will also consider their environmental impact on a life cycle basis [18]. The largest emitters in harbours are ships, more specifically their diesel generators. For this reason, an important measure for ports is the introduction of On-shore Power Supply (OPS), which significantly reduces emissions from ships while in port [12]. This also includes pollutants such as noise [19]. If OPS is not possible from an economic point of view, alternative methods must be further researched [20]. OPS will in most cases require electricity from the local grid, which would require costly investments in the local grid or local power generation.

To translate all these measures into a workable model (including the emphasis on OPS), SD Modelling can be used. To date, there are not many studies that have used SD modelling to estimate GHG emissions from shipping. In one case [21], a SD model was developed to reduce GHG emissions from container ships travelling from Shanghai to LA. In another SD model [22], emissions from ships on the Northern Sea Route (NSR) were assessed. In another study [23], emissions from the Qingdao container port were reduced in a SD model. In one more study [24], authors have finalised the decarbonization model for the Port of Koper container terminal by 2050 using SD. Since this study deals with a similar topic in relation to the Port of Koper, the resulting research question is of course: Is it possible to improve the existing model and how? To answer this research question, our aim was to further upgrade the existing model.

## 3 MATERIALS AND METHODS

This study applies a SD approach to the reduction of greenhouse gas emissions from the container terminal in the Port of Koper between 2023 and 2050 with annual time steps. In this way, it is harmonised with the IMO targets in order to achieve the neutrality targets. The base year 2023 is the starting year, as the most recent data was available for this year. SD is an excellent tool for analysing complex relationships between different variables such as economic, technological, technical and political measures, especially over time. This makes it ideal for long-term planning. The study employs a quantitative methodology that uses different emission sources, technology deployment curves and policy measures to provide a comprehensive scenario analysis for decarbonization strategies.

The system boundaries include the following GHG-emitting activities: direct emissions from diesel-powered port equipment and ships, indirect emissions from electricity consumption in the container terminal from the Slovenian power grid and infrastructure emissions from the energy consumption of the container terminal buildings.

The model contains the stock and flow structure of SD models by including the following elements: state variables (equipment size, technology adoption rate, and emission accumulation rate), rate variables (technology adoption rates, efficiency improvements, and emission generation rates), auxiliary variables (throughput growth and regulatory factors), and constants (equipment specifications, operating parameters, and emission factors).

The model integrates five subsystems: The economic subsystem, which accounts for the increase in container throughput; the technological subsystem, which includes equipment electrification rates, the introduction of alternative fuels and efficiency improvements; the regulatory subsystem, which includes IMO regulations and emission reduction targets; the operational subsystem, which includes equipment utilisation along with maintenance and replacement cycles; and the environmental subsystem with its emission calculations and decarbonization of the network.

The data for port equipment, such as emission factors and working hours, were mainly taken from the article [24]. The ship data was provided to us by the harbour authorities of the Port of Koper. In terms of maritime regulations and targets, the primary source was the IMO [25].

Technology adoption rates follow logistic S-curve functions to represent realistic technology penetration patterns:

$$\text{Adoption Rate} = \frac{1}{1 + e^{(-k(t-x_0))}} \quad (1)$$

k = adoption rate parameter (technology-specific)

t = time index

$x_0$  = inflection point (50% adoption time)

The model was programmed using the Python programming language. NumPy was used for numerical calculations and array operations. We used SciPy to interpolate functions for parameter trajectories. Matplotlib visualised the data and presented the results. Pandas completed the management and analysis of the data structures.

The simulation uses discrete time integration with annual time steps and calculates the emissions generated by the equipment based on emission factors and working hours, the introduction of technologies with S-curve functions, the transition from conventional fuels to alternative fuels and the development of emission values.

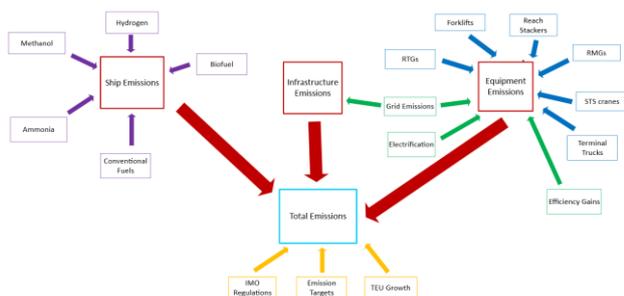


Figure 1. The Basic Flowchart of Model Variables

## 4 RESULTS

Based on the assumed parameters and the data provided by the port authorities, we have estimated the total GHG emissions of the container terminal in the Port of Koper in 2023 at approximately 25,047 tonnes CO<sub>2</sub>EQ. The emissions are distributed as follows: 69.2% of total emissions are from port equipment, 30.0% from vessels and 0.8% from infrastructure systems. Port equipment emissions are divided into the following categories: Straddle carriers produce 5,581 tonnes of CO<sub>2</sub>EQ (22.3% of total emissions), terminal trucks contribute 5,644 tonnes of CO<sub>2</sub>EQ (22.5% of total emissions), RTG cranes 4,725 tonnes of CO<sub>2</sub>EQ (18.9% of total emissions), STS cranes 320 tonnes of CO<sub>2</sub>EQ (1.3% of total emissions). Other port equipment contributes 1,040 tonnes CO<sub>2</sub>EQ (4.2% of all emissions). STS cranes have low total emissions as they are fully electrified. We have estimated ship emissions at the Port of Koper container terminal at around 7,500 tonnes CO<sub>2</sub>EQ.

This model shows significant reductions in total emissions, from 25,047 tonnes CO<sub>2</sub>EQ in 2023 to 2,847 tonnes CO<sub>2</sub>EQ in 2050, which corresponds to a reduction in total emissions of 88.6. The emission reductions follow a non-linear pattern. By 2030, total emissions will fall to 22,156 tonnes CO<sub>2</sub>EQ (11.5% less than in 2023), by 2040 total emissions will amount to 9,823 tonnes CO<sub>2</sub>EQ (60.78% less than in 2023) and by 2050 they will reach 2,847 tonnes CO<sub>2</sub>EQ (88.63% less than in 2023), thus coming very close to decarbonization.

The Equipment emission reductions show the highest reduction level, from 17,310 tonnes CO<sub>2</sub>EQ in 2023 to 1,205 tonnes CO<sub>2</sub>EQ in 2050 (93% reduction). This is primarily due to electrification (78% electrification of diesel appliances by 2050), decarbonisation of the grid, which reaches 0.01 tonnes CO<sub>2</sub>EQ /MWh [26], and efficiency improvements of 30% [27].

Emissions from shipping are gradually decreasing, from 7,500 tonnes CO<sub>2</sub>EQ in 2023 to 1,598 tonnes CO<sub>2</sub>EQ (78.7% reduction). This is primarily due to the introduction of alternative fuels (85% adoption rate), the introduction of OPS (95% adoption rate) and the improvement of ship efficiency (up to 30% improvement) [28]. The adoption of alternative fuels is divided into an adoption rate of 30% for ammonia, 25% for methanol, 15% for biofuels and 15% for hydrogen.

Infrastructure emissions fall from 237 tonnes CO<sub>2</sub>EQ in 2023 to 44 tonnes CO<sub>2</sub>EQ in 2050 (81.4% reduction). This is achieved primarily through the decarbonization of the grid.

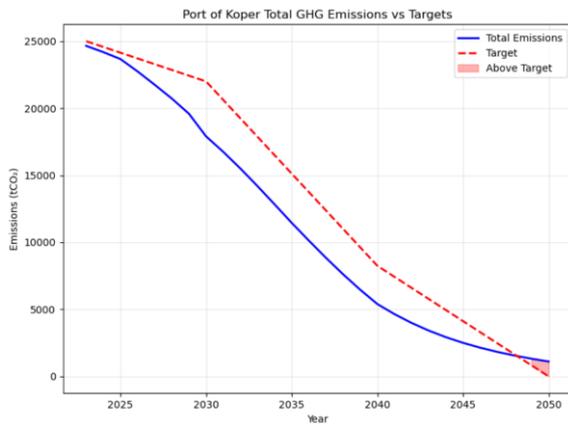


Figure 2. Modelled trajectory versus IMO targets

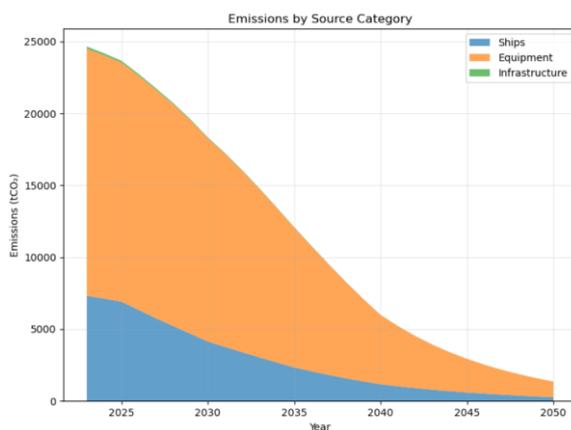


Figure 3. Contribution of total emissions by each subsystem through timeline in the model

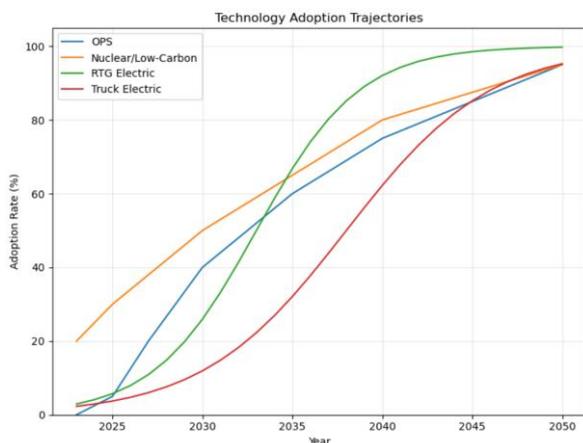


Figure 4. Adoption rate of main decarbonization measures throughout the timeline

## 5 DISCUSSION

This SD model is in some respects an improvement on Model 1 and Model 2 [24], which were produced in another study. The new study offers a more complex approach in which emission sources and mitigation measures operate in a more interconnected system and to a lesser extent as independent variables.

The S-curves of the adoption functions of the current SD model are more realistic than the linear adoption rates in the earlier Model 1 and Model 2. These logistic curves depict the slow initial adoption, rapid scaling phase, and eventual market saturation

typical of real-world technology adoption. The same path is followed by the total emission reductions of the current model (gradual decline from 2023 to 2030, accelerated reduction from 2040 to 2050 and strong decarbonization from 2040 to 2050).

In this model, fuel transition is also more diverse. In addition to ammonia, hydrogen and methanol, we have also added biofuels as a potential, albeit only partial, substitute for fossil fuels.

We have also included the integration of throughput growth in the model, with an annual increase in container throughput of 2.5%, which is more realistic compared to static throughput. For an accurate assessment of the increase in container throughput, we would need more data from the port authorities.

However, the new, improved model has some limitations. The model requires real and not estimated input data, which must be constantly updated over time. The sophisticated interactions of the model are more sensitive to parameter calibration errors. Future models could be improved by waste heat utilisation, material recycling and circular economy projections.

Despite its limitations, the model can be transferred to other ports by adapting the framework and variables, preserving the structural relationships and providing a template that can be effectively customised and extended. The best thing about this model is that it can be constantly updated with new insights and new technologies that are not yet on the market, with new variables in real time.

## 6 CONCLUSION

The SD model developed for the container terminal of the Port of Koper shows that large emission reductions can be achieved by coordinating different SD variables, such as technology adoption and policy adaptation. While the approximate emission reduction of 88.6% by 2050 is not a complete decarbonization, being slightly short of it, it represents a realistic path to a net-zero target when ambitions and operational requirements are taken into account.

The most important thing about this model is the fact that the integrated technology assessment and regulatory compliance provide a basis for planning future strategies and decisions that could bring the Port of Koper to the forefront of sustainable port operations. The integrated approach is far more effective compared to traditional linear models as it allows for more accurate forecasts.

Although achieving full decarbonization will require further improvements and perhaps even the addition of new variables by 2050, the model is an excellent template for a future roadmap towards this goal. The 2,847 tonnes of CO<sub>2</sub>EQ remaining in 2050 could be an opportunity for further research and additional measures such as carbon capture and faster integration of nuclear energy into the grid.

This study shows that ports can lead the way in decarbonising maritime transport through sheer planning, new technologies and collaboration. The Port of Koper's science-based decarbonization planning,

underpinned by sophisticated modelling, could contribute to global emissions reduction in the port industry.

The transition to a carbon-neutral port operation is also a strategic opportunity, not only for the environment, but also for further efficiency gains, improved competitiveness through innovation and collaboration. In this way, the Port of Koper can achieve its decarbonization goals while remaining an important port of entry for Central Europe.

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