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Corridor Scale Planning of Bunker Infrastructure for Zero-Emission Energy Sources in Inland Waterway Transport

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Abstract. The availability of supporting bunker infrastructure for zero-emission energy sources will be key to accommodate zero-emission inland waterway transport (IWT). However, it remains unclear which (mix of) zero-emission energy sources to prepare for, and how to plan the bunker infrastructure in relative positions and required capacity at corridor scale. To provide insight into the positioning and dimensions of bunkering infrastructure we propose a bottom-up energy consumption method combined with agent based network simulation. In the method, we first produce a two-way traffic energy consumption map, aggregated from the energy footprint of individual vessels on the transport network. Next we investigate the potential sailing range of the vessels on the network if they would sail the same routes, but with alternative energy carriers. Based on the sailing range of the vessels for different energy carriers, the maximum inter-distance between refuelling points can be estimated. By aggregating the energy consumptions of all the vessels on the network, we can estimate the required capacity of a given refuelling point. To demonstrate the basic functionality we implement the method to four representative corridor scale inland shipping examples using zero-emission energy sources including hydrogen, batteries, e-NH3, e-methanol and e-LNG. The application in this paper is limited to four abstract cases. A recommended next step is to apply this approach to a more realistic network.

Keywords: Inland waterway transport · Zero-emission · Bunkering infrastructure · Sustainable energy sources · Energy consumption

1 Introduction

The world's economy relies heavily on waterborne supply chains. Approx. 80% of all global trade is shipped by marine transport; according to UNCTAD (2021) subdivided into tanker trade (2020: 2,918 106 tons loaded), main bulk (2020: 3,181 106 tons loaded) and other dry cargo (2020: 4,549 106 tons loaded, of which a little over 40% is attributed to container transport). Overall efficiency of global supply chains is to a great

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extent determined by the inland transport networks they are connected with. Approximately one third of the operating cost of vessels is related to energy use.

The Paris Climate Agreement, and its subsequent implementation, a.o. by the International Maritime Organization (IMO), requires significant changes in power systems on board (engine room, energy storage). These changes will not only affect the performance of individual vessels (e.g. loading capacity, range, velocity), but also the performance of ports and waterway networks (e.g. allocation of bunker stations, development of the new fuel supply network, potential modal shift, network inter-competitiveness).

A major challenge that is currently hindering the energy transition is the lack of insight in how alternative power source strategies on board of individual vessels cascade through a ports and waterways system, ultimately impacting its overall competitive performance. A recent first step was the development of a method enabling corridor scale estimation of inland shipping related energy consumption, fuel use and emission patterns (Jiang et al. 2022b). A logical next step is to develop a method that builds on these energy consumption and fuel use patterns to support the rational design of bunkering networks (per energy carrier estimate a logical maximum inter-distance between bunkering stations and their respective required total capacity).

2 Method

When the transport demand (volumes, origins, destinations), the state of the waterway network (e.g., water depths, currents), and the state of the fleet (composition, engine ages, etc.) are known, the associated energy demand for transport can be estimated using vessel resistance algorithms (Bolt 2003; Hekkenberg 2013; Vehmeijer 2019; Segers 2021; Van Koningsveld et al. 2021, Rijkswaterstaat 2022a; Rijkswaterstaat 2022b).

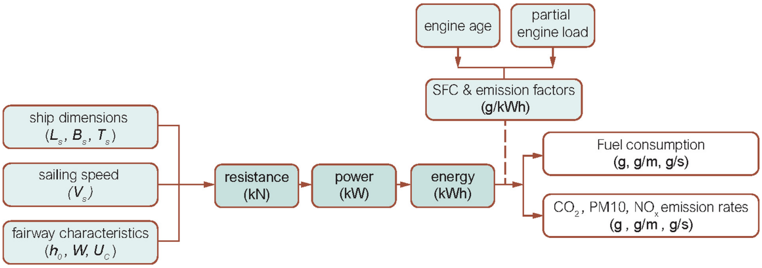


Fig. 1. Methodology for estimating emissions for IWT vessels (image modified from Segers 2021, by TU Delft Ports and Waterways is licenced under CC BY-NC-SA 4.0)

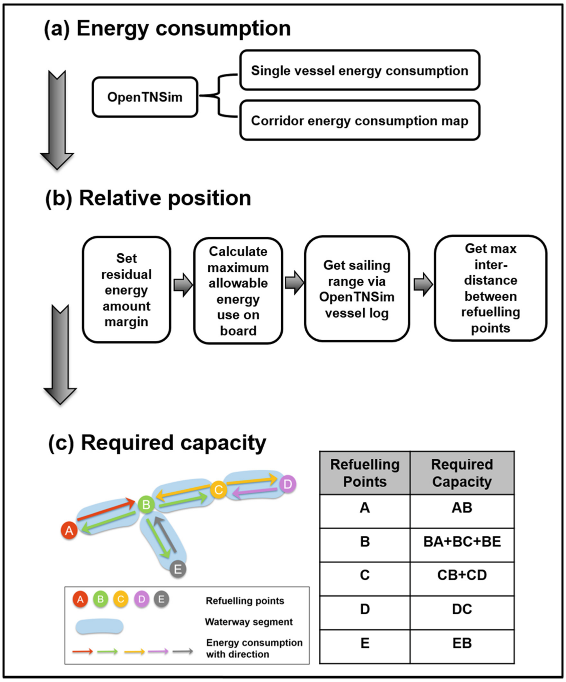
Figure 1 describes the methodology for estimating emissions for IWT vessels. Starting point of the analysis are the ship dimensions (length at the waterline (L_s), beam (B_s) and actual draught (T_s)), the vessel sailing speed (V_s) relative to the water, and the waterway characteristics (water depth (h_0), waterway width (W), current (U_c)). With this information, based on Holtrop and Mennen's method (1982) with Zeng et al.'s (2018) shallow water effect correction, we can estimate the total resistance a vessel experiences while sailing at a given velocity with respect to the water. Once the total resistance (kN) is calculated we estimate the total power (kW) that is required to overcome this resistance, which includes the power for propulsion and hotel system. Next we calculate the energy (kWh) that is consumed by multiplying this total power with the duration of its application. The energy consumption estimate can then be translated to fuel use and emissions.

Segers (2021), showed how this approach can be used to estimate corridor scale energy consumption, fuel use and emission patterns; both to estimate current patterns, using position information from the Automatic Identification System (AIS) that vessels need to have on board, and future patterns under various scenarios and policies. Jiang et al. (2022b) further generalized the approach by Segers (2021) to come to an approach that in principle is world-wide applicable (provided the required input data can be provided of course). A logical next step is to use this method to estimate energy consumption and fuel use to inform decision making on bunker infrastructure, both placement and capacity. Figure 2 displays the method we propose in this paper to plan a corridor scale bunkering infrastructure in terms of relative positions and required capacity for IWT.

The relative position of a refueling point is related to the sailing range (m) of the fleet, which depends on the total amount of energy storage (kWh) on board and the energy consumption per meter (kWh/m). The required capacity of the refueling points can be estimated based on the total energy consumption (kWh) of the ships between the refueling points.

As a fundamental step, the energy consumption calculation algorithm for a single ship and the whole corridor network has been written into the Python package Open source Transport Network Simulation (OpenTNSim) version v1.1.2 (Jiang et al. 2022a), which enables the further determination of the relative position and required capacity of refueling points in corridor scale.

The following sections describe (1) OpenTNSim simulation with an energy module and how the energy consumption algorithm can be applied using OpenTNSim, (2) how energy consumption maps can be used to rationalize the relative positions of bunker stations, and (3) how energy distribution over the shipping network can be used to define the required capacity of bunker stations.



Refuelling Points	Required Capacity
A	AB
B	BA+BC+BE
C	CB+CD
D	DC
E	EB

Fig. 2. Schematic diagram of the method

2.1 Energy Consumption

2.1.1 OpenTNSim

OpenTNSim is a python package for the investigation of traffic behaviour on networks. It can be used to investigate how water transport chains interact with the waterway network and its infrastructure. Simulations can be used to compare the consequences of traffic scenarios and network configurations (Van Koningsveld and Den Uijl 2020). In this paper we use OpenTNSim version v1.1.2 (Jiang et al. 2022a) (which includes an energy module) to perform energy consumption estimation and determine the relative positions and required capacity of refueling points. The energy module contains ‘resistance, power and energy consumption estimation’ algorithm, that can be applied to consecutive *dx/dt* events from either actual position data (AIS data, trip logs, etc.) or simulated position data (e.g. discrete event simulation output). This enables us to resolve footprints as a function of space and time. The model simulation mainly includes three components:

- Vessel objects with properties (including sailing log information).
- A graph that contains nodes and edges to represent the waterway network. The nodes linked by edges, contain geo-locations (longitude and latitude) of the waterways. The edges are made bi-directional to allow for two-way traffic, and contain waterway characteristics in the edge information.
- A simulation environment for sailing event simulation.

2.1.2 Energy Consumption Estimation in OpenTNSim

The general steps for the energy consumption estimation for a single vessel in OpenTNSim are as follows. First we create a vessel with its vessel properties, mainly include vessel dimensions, vessel sailing speed relative to the water, vessel installed engine power, etc. Then we create a graph with nodes linked by edges composing a network. We use nodes position to represent the geo-locations (longitude and latitude) of waterways. The waterway characteristics which cover the water depth, waterway width, and current speed are contained on each linking edge as edge information. Then we define the route (which is 'path' in the graph) that the vessel will sail. The path is defined by providing the origin and destination nodes in Dijkstra's path algorithm to find the shortest paths. Next we make an environment and add the created graph to the environment. Then we add the created vessel, to which we will append the environment and the route. Lastly, we give the vessel the process of moving from the origin to the destination of the defined path. We incorporate the energy module to this moving vessel, and via this energy module, the resistance, power and energy consumption of the moving vessel are successively calculated per edge along the path. Summing up the energy consumption of all the edges, the total energy consumption along the route can be obtained. Energy consumption in time and space of the vessel can also be mapped via displaying the energy consumption of all the edges along the route together.

The energy consumption of the corridor network can be mapped by aggregating the results of multiple vessels that together represent the corridor's traffic. The corridor energy consumption map is composed of the geographic waterway network, the energy consumption of ships per sailing edge aggregated in space along the waterways, the energy consumption directions according to the ship sailing directions, and the energy consumption in different time scales such as daily, weekly, monthly, seasonally and yearly (for the determination of required capacity for refueling points in different time scales).

2.2 Relative Position

The refueling points are positioned according to the minimum sailing range of the representative fleet (PROMINENT 2016; MOT 2022) in the corridor. The minimum sailing range provides an indicator for the maximum inter-distance between two refueling points, as this minimum value allows all types of ships in the corridor to arrive at the next refueling point. For the minimum sailing range determination, in OpenTNSim, we define vessels with a 'fuel volume', each discrete event we calculate how much energy is consumed and how much fuel. This volume can then be subtracted from the fuel volume. The fuel tank slowly depletes along with the sailing. When a certain 'buffer' is reached this can be defined as the sailing range by that vessel for the given fuel and given the volume of the fuel tank. Then by doing this for various vessels we can find the minimum range. The inter-distance between bunker points should not be larger than this minimum range. It should be noted that the maximum allowable energy use amount is smaller than the total amount of energy storage on board, since we set a residual energy margin which is 5–10% of the total energy storage on board, to prevent the ships running out of all the fuels on board before reaching the next refueling point. The total amount of energy storage can be determined by knowing the mass or volume of zero-emission energy sources on board, energy density and energy conversion system efficiency.

2.3 Required Capacity

Once refueling points are positioned on the corridor energy consumption map, the required capacity of each refueling point can be estimated based on the total energy consumption at various time scales. As shown in Fig. 2(c), the waterway network is divided into waterway segments by the refueling points. As a first scenario we put one refueling station is 'in charge' of all the waterway segments it directly connects. However, to prevent overlapping energy supply for the same segment by the two refueling points at both ends, we allocate the required energy supply amount according to the energy consumption direction, as shown in the refueling points capacity table in Fig. 2(c).

3 Results

Zero-emission energy sources in this paper refers to (green) hydrogen, e-fuels, and batteries. Among which, e-fuels are produced from electricity, water and carbon dioxide or nitrogen. When using electricity from renewable sources and circular carbon dioxide (e.g. from biomass or direct capture from the air), net emissions are near zero (Van Kranenburg et al. 2020). The e-fuels analyzed here include e-NH3, e-methanol and e-LNG.

Although there are increasing number of vessels powered by zero-emission energy sources in recent years (Arief and Fathalah 2022), the energy storage and conversion systems for zero-emission energy sources on board for wide use are still in designing stages (de Vos et al. 2018; de Vos 2020; van Kranenburg et al. 2020; Huang et al. 2021). Therefore, there is no certain value of the total storage amount for zero-emission energy sources on board to refer to. This forms an obstacle to get the sailing range of a zero-emission energy source powered vessel, which in turn hinders the determination of the relative positions and required capacities of the refuelling points. However, with the method implemented in OpenTNSim, we could calculate the required amount of energy (in kWh) and zero- emission energy sources (in kg and m^3) of a vessel sailing on a route to give some insight on designing the energy storage volume on board and preparing the energy amount for the whole route and corridor network.

Via the investigation of inland waterway characteristics (MOT 2022; RVW 2020; CCNR 2021), we have simulated the energy consumption of a motor vessel (M8 type (RVM 2020)) sailing in the corridor network along four distinct routes using OpenTNSim. The vessel properties and waterway network with characteristics are shown in Fig. 3. With the same total sailing distance of 450 km, Route 1 starts from Node 0, through Nodes 1, 2, 3 to Node 4, representing an 'unrestricted waterway' from sea port to the hinterland. Route 2 starts from Node 0 through Nodes 1, 2, 5 to Node 6, representing a route from sea port to the hinterland that includes a ‘shallower section (150 km)’. Route 3 starts from Node 0 through Nodes 1, 2, 7 to Node 8, representing a route from sea port to the hinterland that includes a ‘very shallow section (150 km)’. Route 4 starts from Node 0, through Nodes 1, 2, 9 to Node 10, representing a route from sea port to the hinterland that includes a ‘very shallow section (25 km)’. At routes 1 and 2, the M8 vessel is able to sail with its maximum draught. However, at routes 3 and 4, the M8 vessel has to reduce cargo to gain a smaller draught to pass the limited water depth waterway sections.

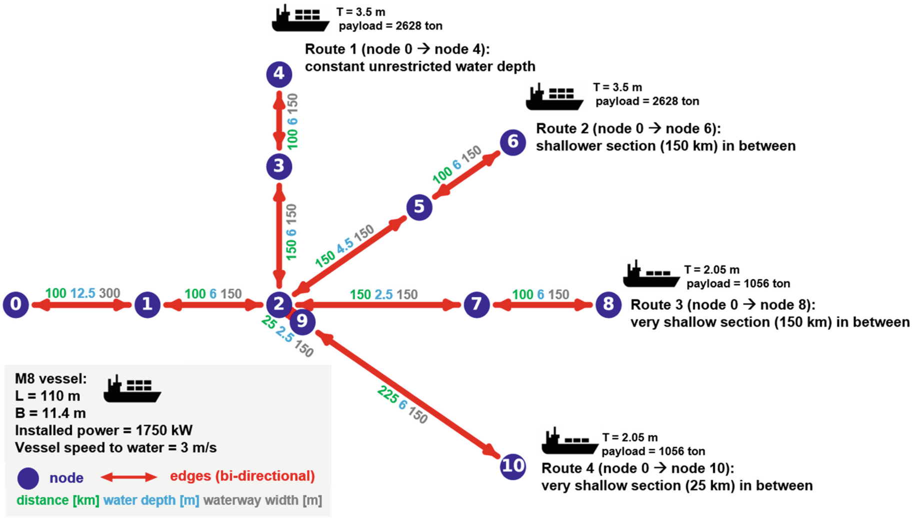


Fig. 3. OpenTNSim input: vessel properties and graph information.

Knowing the net energy gravimetric density (kWh/kg) and net energy volumetric (kWh/m^3) density for zero emission energy sources and the corresponding energy conversion system efficiency, the amount of energy consumption on board can be translated to the amount of zero emission energy sources consumption in mass and volume on board.

The required amount of energy and zero-emission energy sources (in mass and volume) along the route of the M8 vessel estimated via OpenTNSim, are shown in Table 1.

Table 1. The required amount of energy and zero emission energy sources (in mass and volume) along the route

	Required energy amount (MWh)		**Required amount of zero emission energy sources (for fuel only, excludes storage system)**					
			Hydrogen (liquid, -253℃)	E–NH3 (liquid, -34℃)	E–methanol (liquid)	E – LNG (liquid)	Battery 2 MWh (20ft Containers)	Diesel
Route 1: constant unrestricted water depth	13.12	Mass (ton)	1.02	6.55	6.13	2.35		3.48
Payload: 2628 ton		Volume (m^3)	13.26	8.65	7.72	5.84	10.4 containers	4.77
Route 2: with	13.35	Mass (ton)	1.03	6.66	6.22	2.39		3.53
shallower section (150km) **Payload:** 2628 ton		Volume (m^3)	13.47	8.79	7.84	5.93	10.6 containers	4.85
Route 3: with very shallow section (150km)	13.18	Mass (ton)	1.02	6.57	6.14	2.36		3.49
Payload: 1056 ton		Volume (m^3)	13.28	8.67	7.74	5.85	10.5 containers	4.78
Route 4: with very shallow section	11.36	Mass (ton)	0.89	5.74	5.37	2.06		3.05
(25 km) **Payload:** 1056 ton		Volume (m^3)	11.61	7.58	6.76	5.12	9.2 containers	4.18

As shown in Table 1, with the same sailing distance (450 km (Fig. 3)) and same payload (2628 ton), the required energy amount and the required amount of each zero-emission energy source for Route 1 and Route 2 are different. The required energy amount for Route 2 with a shallower section is 0.23 MWh higher than it for Route 1, as more energy is needed to overcome higher sailing resistance in the shallower section. Similarly, the required energy amount for Route 3 is 1.82 MWh higher than Route 4 though with the same sailing distance (450 km) and reduced payload (1056 ton), which is due to the longer 'very shallow section' in Route 3.

In general, for each route, the required mass of zero-emission energy sources in order from smallest to largest are: hydrogen (liquid, −253 °C), E–LNG (liquid), E-methanol (liquid), E–NH3 (liquid, −34 °C), battery with 2 MWh capacity (20ft Containers). The required volume of zero-emission energy sources in order from smallest to largest are: E–LNG (liquid), E- methanol (liquid), E–NH3 (liquid, −34 °C), hydrogen (liquid, −253 °C), battery with 2 MWh capacity (20ft Containers).

For Route 1, it requires 1.02 ton of hydrogen (liquid, −253 °C), which is the lowest mass among other zero emission energy sources. However, the practical constraints on board of a ship are not so much mass, but volume. The required volume of hydrogen (liquid, −253 °C) is the highest among others, 13.26 m^3, which is 2.78 times than required diesel volume. Considering its packing factor, 2, on a ship, the actual required space would be 26.52 m^3, 7.7 times higher than diesel (Van Kranenburg et al. 2020). If its storage space is designed to be of the same size as a diesel tank, with the consideration of 10% residual energy margin on board, then at least 9 bunker points along Route 1 are needed for the vessel to refuel. If its storage space is designed the double size as diesel tank (meanwhile less cargo on board can be taken), with the consideration of 10% residual energy margin on board, then at least 5 bunker points along Route 1 are needed for the vessel to refuel.

The required amount of E–NH3 (liquid, −34 °C) and E- methanol (liquid) are similar both in mass and volume, with E–NH3 is slightly higher. Considering the packing factors, which are 1.1 and 1 respectively, for Route 1, the actual required storage space on board of E–NH3 (liquid, −34 °C) and E- methanol (liquid) are 9.51 m^3 and 7.72 m^3, respectively.

There is only a small difference between the required fuel amount of E–LNG (liquid) and diesel. The required fuel amount of E–LNG (liquid) for Route 1 in mass is 1.13 ton less than diesel, in volume is 1.07 m^3 more than diesel. The packing factor of E– LNG (liquid) is 2 times higher than diesel, which leads to 2.14 m^3 of extra required storage space than diesel on board.

For Route 1, the required number of battery containers with 2 MWh capacity (in 20ft container), considering 10% residual energy margin, is 12. If the M8 vessel takes 2 battery containers on board, at least 6 docking stations along the route are needed; if the M8 vessel takes 4 battery containers on board, then at least 3 docking stations along the route are needed. It should also be noted that the payload capacity onboard is reduced due to more battery containers.

4 Discussion

To estimate the energy amount for the whole route and corridor network, the reliable quantification of energy demand (kWh) is needed. It should be observed that even the same vessel type with the same payload (ton) and sailing distance (km) oftentimes results in different energy consumption patterns along the route due to different sailing situations such as water depth variation as shown in the Results. Therefore, it is essential to consider waterway characteristics along the route to get reliable quantification of energy demand of an individual vessel and the whole corridor.

The data availability may hinder the wider use of the method, as it requires quite some input data: on the state of the IWT network (water depth, ambient currents, waterway classes, available routes), on the state of the vessel fleet (vessel speeds to the water, vessel dimensions, payload levels, actual draughts, installed engine power), origin - destination information, etc. However, recently much of this information is gathered and disseminated by authorities, which greatly enhances the data availability. Changjiang Waterway Bureau (China), for example, provides Changjiang Waterway electronic map including a comprehensive description of waterway characteristics for public free use. Pearl River Administration of Navigational Affairs (China) publishes daily number of ships passing through locks in Pearl River with sailing directions and payload information. Rijkswaterstaat (The Netherlands) hosts Vaarweginformatie.nl, where a lot of crucial information on the water transport network is disseminated and kept up to date. Other countries undertake similar efforts, a.o. in European projects. Realistic vessel speeds (relative to the ground), for the sailing events, can be obtained from AIS data (ship geographic position time series). Combined with data on ambient currents, vessels speeds relative to the water can be estimated. When detailed information is hard to come by, averages or probability distributions may be useful to provide insight.

As this method implemented in OpenTNSim is able to quantify the required energy amount of both an individual vessel and the whole corridor network with various water depths, current, payload, and sailing speed, vessel types and amount, etc., it can be used for designing bunker infrastructure with various scenarios including extreme discharge scenarios, concerning environment and economy changes. However, as the bunker locations in practice is selected not merely based on energy demand but also other societal considerations, this method should not be used to really find the exact locations of bunker points, but rather to make sure that the bunker points are located at a reasonable spacing given the vessels, their fuel tanks and energy carriers.

5 Conclusions and Recommendations

This paper proposes a bottom-up method implemented in the agent-based transport simulation, OpenTNSim, for corridor scale planning of bunker infrastructure for zero-emission energy sources (hydrogen, batteries, e-NH3, e-methanol and e-LNG) in IWT. It focuses on the positioning and dimensions of bunkering points based on vessel energy consumption in the corridor.

Taking vessel properties and waterway characteristics into account for energy consumption estimation, the method is applied to four distinct IWT routing examples, in which the variation of the energy demand (MWh) for an individual M8 vessel sailing at routes with same sailing distance (km) and payload (ton) conditions is revealed. The total required amount for each zero-emission energy source in mass and volume (number of containers for batteries) is also calculated and analysed. The application examples provide insight into designing the energy storage volume on board, preparing the number of bunkering points and total energy amount for the whole route and corridor network.

The method is recommended to be applied to map corridor two-way traffic energy consumption in time and space with actual data such as AIS data, trip log and the depth, width, and current information of waterway network. Then with the value of suitable energy storage space on board for different vessel types as input, derive the sailing range via OpenTNSim for the determination of relative positions of bunkering points, and finally estimate the required capacity in various time scales of bunkering points in the corridor network.

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References

Arief IS, Fathalah AZM (2022) Review of alternative energy resource for the future ship power. In: IOP conference series: earth environmental science, vol 972, p 012073

Bolt E (2003) Schatting energiegebruik binnenvaartschepen. Technical report. Rijkswaterstaat Adviesdienst Verkeer en Vervoer, Rotterdam

CCNR (2021) "Act now!" on low water and effects on Rhine navigation. https://www.ccr-zkr.org/files/documents/workshops/wrshp261119/ien20_06en.pdf

De Vos P (2020) AmmoniaDrive: a solution for zero-emission shipping?! SWZ Maritime 141 (3):36–37

De Vos P, Stapersma D, Duchateau E, van Oers B (2018) Design space exploration for on-board energy distribution systems: a new case study. In: Bertram V (ed) Proceedings of the 17th international conference on computer and IT applications in the maritime industries (COMPIT 2018), pp 463–481. Technische Universität Hamburg-Harburg

Hekkenberg R (2013) Inland ships for efficient transport chains. Ph.D. thesis. Delft University of Technology

Holtrop J, Mennen GGJ (1982) An approximate power prediction method. Int Shipbuilding Prog 29:166–170

Huang MY, He W, Incecik A, Cichon A, Królczyk G, Li ZX (2021) Renewable energy storage and sustainable design of hybrid energy powered ships: a case study. J Energy Storage 43:103266. https://doi.org/10.1016/j.est.2021.103266

Jiang M, Segers LM, Van der Werff SE, Baart F, Van Koningsveld M (2022a) OpenTNSim (v1.1.2). Zenodo. https://doi.org/10.5281/zenodo.6447088

Jiang M, Segers LM, Van der Werff SE, Hekkenberg R, Van Koningsveld M (2022b) Quantification of energy consumption, fuel use, and emissions for sustainable inland shipping (submitted)

MOT (Ministry of Transport of the People's Republic of China) (2022) Navigation Standard of Yangtze River Trunk Line. https://wtis.mot.gov.cn/syportalapply/sysnoticezl/indexzl (in Chinese)

PROMINENT (2016) Identification of the fleet, typical fleet families & operational profiles on European inland waterways. https://www.prominent-iwt.eu/wp-content/uploads/2015/06/2015_09_23_PROMINENT_D1.1-List-of-operational-profiles-and-fleet-families.pdf

Rijkswaterstaat (2022a) BIVAS. https://bivas.chartasoftware.com/Home

Rijkswaterstaat (2022b) BIVAS: emissies. https://bivas.chartasoftware.com/Home/BIVASApplicatie/Documentatie/Emissies/

RVW (2020) Richtlijnen Vaarwegen 2020. Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat. https://puc.overheid.nl/rijkswaterstaat/doc/PUC_632307_31/1/

Segers L (2021) Mapping inland shipping emissions in time and space for the benefit of emission policy development: a case study on the Rotterdam-Antwerp corridor. Master's thesis

UNCTAD (2021) Review of Maritime Transport 2021. https://unctad.org/webflyer/review-maritime-transport-2021

Van Koningsveld M, Den Uijl J (2020) OpenTNSim (Version 1.0.0). https://github.com/TUDelft-CITG/OpenTNSim/. https://doi.org/10.5281/zenodo.3813871

Van Koningsveld M, Verheij H, Taneja P, de Vriend H (2021) Ports and waterways: navigating the changing world. Delft University of Technology. https://doi.org/10.5074/T.2021.004

Van Kranenburg K et al (2020) E-fuels: towards a more sustainable future for truck transport, shipping and aviation. TNO report

Vehmeijer L (2019) Measures for the reduction of CO_2 emissions, by the inland shipping fleet, on the Rotterdam-Antwerp corridor. Master's thesis. Delft University of Technology

Zeng Q, Thill C, Hekkenberg R, Rotteveel E (2018) A modification of the ITTC57 correlation line for shallow water. J Mar Sci Technol 24(2):642–657. https://doi.org/10.1007/s00773-018-0578-7