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Milan Kalajdžić
Matija Vasilev
Nikola Momčilović

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Inland waterway cargo vessel energy efficiency in operation

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Summary

Inland waterways vessels (IWV) have no mandatory regulations regarding their energy efficiency, as sea-going ships have. So far, there are just two proposed design energy efficiency evaluation methods, both based on IMO EEDI approach and data on EU inland navigation. Operational indicators and real-time navigation measurements from available literature do not exist. Therefore, this paper aims to introduce the energy efficiency in operation (EEO), assessed for the typical Danube cargo vessel. Firstly, an operational profile is acquired by tracking the vessel's voyages, and by identifying actual constraints of each sector the vessel has sailed during the designated time. Secondly, EEO is incorporated within two available methods and calculated based on acquired operational data considering different navigational conditions. The paper shows how the energy efficiency vastly depends on variables such as water depth, current speed, draught, deadweight, river constraints. Analysis is performed for the most employed month of the vessel navigation, and annually. Depending on water level scenarios and during the selected month of sailing, the total amount of CO_2 emitted is estimated to be between 22.7 t and 29.9 t, while the necessary average speed reduction (i.e., slow steaming) per sectoral voyage for the requirement compliance is calculated to be in between 4.8%-26%. Slow steaming is assessed to extend the time of voyage for 6.1-10.7 hours on monthly basis and 49-87 hours annually.

Key words: *energy efficiency design index; energy efficiency in operation; inland vessel efficiency, inland waterway vessels; operational profile, slow steaming.*

1. Introduction

Energy efficiency indicators for sea-going ships intended for international voyages are used for a decade and are provided by the International Maritime Organization (IMO). They can be divided into design and operational ones. Firstly, a design indicator labelled as energy efficiency design index (EEDI) became mandatory for new ships over 400 GT built between 2013 and 2015 [1], under the MARPOL Annex VI. EEDI criterion has been strengthened over the years, namely in 2015, 2020, and expected to be strengthened in 2025. In 2023, existing ships faced the IMO's regulatory examination through the compulsory requirements of the energy efficiency existing ship index (EEXI), see calculation guidelines in [2]. The main disadvantage of the design-based indicators is that they do not represent an actual navigational nature of shipping. They use design or nominal inputs, acquired as a single value from the calculation procedures defined in [1, 2]. Therefore, energy efficiency is evaluated using single value for deadweight (DWT), speed, engine power, etc. In order to represent the real sailing conditions during the voyages over a period of time, a carbon intensity indicator (CII) has been set as mandatory measure starting from 2023 [3]. CII is an operational indicator applied for ships over 5000 GT and is projected to provide an actual operational emission estimation. Based on CII results obtained for the whole year, ships will be rated by grades: A, B, C, D, E (A – the highest grade, E – the lowest grade). Ship with lower annual rating (for instance, D or E) must provide a plan to improve rating and its energy efficiency. Fortunately, fuel consumption recording during the navigation has become mandatory from 2019, for ships over 5000 GT, as set by IMO. It is achieved by implementing the data collection system (DCS) [4]. Moreover, IMO has already provided an operational tool (although not an actual criterion and not mandatory) called energy efficiency operational indicator (EEOI) [5]. EEOI is planned to help ship operators to supervise the energy efficiency performance of their fleets over time and thus, to identify increased emission sequences and to quantify the effect of modifications on their voyage efficiency. All these indicators' aims were to provide short-term measures in order to achieve mid- and long-term greenhouse gas (GHG) reduction goals, which IMO presented in its studies. Most recent study from 2020 [6] targeted the following: to reduce CO_2 emissions per transport work (carbon intensity) in shipping, on average, to 40% until 2030 (compared to 2008), to reduce emissions per transport work (carbon intensity) in shipping, on average, to 70% until 2050 (compared to 2008), to achieve peak emissions from shipping as soon as possible, and to reduce annual GHG emissions from shipping to at least 50% until 2050, (compared to 2008). Literature data on energy efficiency of ships followed the regulation adoption and have been increasing over the years. Energy efficiency level for most prominent multipurpose ships and bulk carriers built from 2000 until 2020 is evaluated in [7, 8], respectively. As slow steaming has become the most used operational measure to improve EEDI and EEXI levels, paper [9] additionally gave an estimation for the ships' power reduction needs to comply with novel requirements. Slow steaming benefits for various navigation conditions are investigated in [10]. The paper emphasized the importance of considering actual sailing routes for a specific container ship in energy efficiency evaluations. In [11], the real voyage data for general cargo ship were used to estimate CII, based on different engine loads and slow steaming rate. Besides extensively researched slow steaming, some other measures for existing designs have been analysed, such as the influence of biofilm on energy savings [12].

In contrast, inland waterway vessels (IWV) are not regulated by IMO and thus, not falling under their mandatory requirements. Nevertheless, in Europe alone, more than 15000 IWV are in operation, while most of them are registered in Rhine and Danube countries, 63% and 22%, respectively, according to data from 2021 [13]. As of 2017, nearly 40% of the Danube vessels is more than 40 years old, while less than 1% of them are built after 2010 [14]. In Danube countries, the largest quantity of goods carried within national territories is achieved in Romania (37.5%) and Serbia (13.3%) [14]. From 2017 until 2020, the rate of change of goods in major Danube ports in these two countries increased by 10.5%, whereas in all other Danube ports decreased by 7.3%, on average [15]. Dry cargo IWV represent the major ship type, with a 73% share on Rhine, and 76% share on Danube. They compete in freight transport over land with road and rail modes, while sea-going ships have no competition in that sense. Moreover, IWV pass through the large cities and urban areas and are emitting harmful pollutants. Nonetheless, they are considered as a cleaner mode of transport, expressed in ton per km of freight transport, as shown in [16]. Therefore, 2019 EU Green Deal [17] addressed IWV, by implying that around 75% of the road and rail transport should be moved to IWV. Moreover, European Commission's Naiades III action plan from

2020 [18], being in line with EU Green Deal, set a goal to increase inland and short-sea shipping by 25% and 50% until 2030 and 2050, respectively. In order to counter GHG emissions from IWV, Central Commission for the Navigation of the Rhine (CCNR) published a roadmap in 2022, similar to IMO goals [19], in which it was aimed to reduce GHG emissions from IWV by at least 35% until 2035, compared to 2015 level, and to almost eliminate GHG and other pollutant emissions until mid of the century.

Although IWV policies exists from recently, IWV have no mandatory regulations regarding the energy efficiency, except evaluations proposals given in two methods from [20] and [21]. These methods used data on European inland navigation. They are based on IMO EEDI approach; however, they are different in their nature, see detailed their comparison in [22]. Other methods that targeted European waterways are also available, but they are more developed to evaluate transport rather than energy efficiency. Their systematic description and comparison are given in [16].

On the other hand, there were some rare attempts to establish “similar to IMO EEDI” assessments outside European waterways. Energy efficiency attained values and requirement line have been evaluated for rivers in Bangladesh, as they represent important transport path in the region. Study in [23] applied IMO EEDI procedure to general cargo, oil tanker and passenger IWV. It was concluded that EEDI assessments should be region based rather than generalized for the world’s inland fleets, due to the diversity of inland navigation. Furthermore, paper [24] investigated an influence of design features on energy efficiency of IWV. The study concluded that the service speed decrease and draught increase lowered EEDI values, which is in compliance to the European IWV performances, see [16]. These attempts have been revised in [25] to account for the field study performed by measuring actual MCR for 15 IWV. The research stated that the effect of shallow water on energy efficiency of studied IWV is significant, and varied between 19.30% and 21.10%, on average. Other efforts to include energy efficiency in inland navigation has been more directed towards the hydrodynamically optimised design for the particular river with respect to the high flow and low depth constraints, as presented in [26] for Magdalena river in Colombia. To conclude, an average age of IWV on Danube is much larger than in case of sea-going ships. Moreover, IWV are left behind with no compulsory design-based energy efficiency regulations or requirements, while operational ones are also neglected. This can be alarming since IWV include highly diversified operations and large fleets. In addition, literature dealing with energy efficiency of IWV is very rare. There are no available energy efficiency assessments of IWV using instantaneous and actual fairway constraint change, as well as operational data of any kind (real-time, averaged or estimated), as delivered in this paper. Therefore, the objective of this paper is to perform energy efficiency assessments for a typical self-propelled IWV taking into account:

- energy efficiency design indices delivered by two methods proposed so far and given in [20, 21], and
- energy efficiency in operation using operational data for the selected vessel.

2. Assessment methodology

The following methodology for assessments is used for the case study vessel:

- for a year of service, identified are monthly travelled distances,
- a month in which the vessel had the most frequent usage (distance covered) is selected for further analysis,

- input data gathered for evaluation include identification of actual constraints of the fairway on each sector of the navigation and actual speed of the vessel for a selected month of sailing and annually, as elaborated in sect. 2.1.
- energy efficiencies are evaluated based on two methods from [20, 21], and only ones proposed so far for IWV, as given in sect 2.2,
- the total CO_2 emitted by the vessel is evaluated for the selected month of sailing and annually, based on two available methods.
- voyages that did not satisfy energy efficiency requirements has been selected and their energy efficiency in operation is evaluated by the sector,
- the necessary reduction of speed is calculated for the critical voyages (and their corresponding sectoral sailings) to comply with the requirements,
- the additional time for navigation is calculated for the vessel to comply with regulations by means of slow steaming.

Note that the paper is not providing a new method. It is delivering the new approach for inputs for existing methods. It uses operational and not the design data as inputs. Moreover, the paper compares methods based on operational input data for the particular voyage. This is not performed so far in the literature related to IWV. Some of the operational data are obtained in real-time and some, for which authors could not acquire data, are estimated using extreme scenarios, which is thoroughly described in sect. 2.1.

2.1 Operational profile

Compared to sea-going voyages, in general, IWV operational profile is more complex as its navigation additionally considers shallow water effects, current speed, bank effects, the presence of the bridges, etc. The vessel considered in this paper operated on Danube between port of Constanta (Romania) and Aljmas (Croatia), during the period starting from 15 January 2022 until 15 January 2023. The voyage data are extracted from Marine Traffic website [27]. Nonetheless, the data from the website were not sufficient for precise representation of the navigation conditions. Thus, more accurate and detailed pilot charts of Danube are employed. They are published by the Danube Commission in [28] and are included within six documents: Pilot Charts of the Danube I, II, III(1), III(2), IV and V. Pilot charts cover the Danube from its confluence into the Black Sea (0 km) to the Hungarian-Serbian border (1433 km from the confluence). The raw data from the charts are divided into 171 sectors ranging from 2 to 12 km in length, with average sector having 5 km in length. This division was too large to analyse, so simplified river model is created meaning that 171 sectors are regrouped into 20 sectors, separated by major Danube ports. Going upstream, these ports are: Constanta (Romania), Agigea (Romania), Murfatlar (Romania), Medgidia (Romania), Cernavoda (Romania), Silistra (Bulgaria), Ruse/Giurgiu (Bulgaria/Romania), Svishtov (Bulgaria), Vidin/Calafat (Bulgaria/Romania), Prahovo (Serbia), Drobeta Turnu Severin (Romania), Orsova (Romania), Moldova Veche (Romania), Veliko Gradište (Serbia), Smederevo (Serbia), Pancevo (Serbia), Belgrade (Serbia), Sremski Karlovci (Serbia), Novi Sad (Serbia), Vukovar (Croatia), Aljmas (Croatia).

The exact water levels and current speeds during navigation of the vessel could not be obtained from the available data, since there is no available historical data on real-time tracking of such parameters, according to the best of authors knowledge. Hence, navigation is modelled according to the two extreme scenarios in which the vessel could potentially sail:

- during the lowest navigable water levels (LNWL) for the sector and
- during the highest navigable water levels (HNWL) for the sector.

This means that actual vessel water level could have been only evaluated in between these two extreme values of LNWL and HNWL. Both, LNWL and HNWL change as the vessel is passing through the each of the sector. LNWL and HNWL also produce two extreme current speeds. Therefore, by analysing the vessel navigation at LNWL and HNWL (and corresponding current speeds), we assumed that its consequent and actual energy efficiency could have been only evaluated in between two energy efficiencies: one calculated for LNWL and one calculated for HNWL condition. LNWL and HNWL data and their corresponding current speeds are obtained statistically. Namely, data from [28] includes LNWL and HNWL values for every 3 km of the Danube sector. These data were averaged by the sector to obtain each of the sector's average LNWL and HNWL, which is used for further analyses. Correspondingly, the current speeds for both scenarios were determined following the same procedure and sector division. In such way, the energy efficiency of the vessel can be considered to be within the bandwidth given by two extremes. Therefore, the following parameters for the Danube sectors are extracted from [28, 29]: river kilometre, LNWL, HNWL, current speed at LNWL and HNWL. During the period of one year (Fig. 1), the vessel had 106 voyages and covered the distance of 21531 km. Vessel spent 138 days in navigation, 210 days in ports, while during 17 days the vessel was idle. In August 2022, there was no navigation. However, in October 2022, the vessel was most frequently employed and thus, travelled the largest distance compared to other months. Therefore, October 2022 was chosen for detailed assessment. The reason that the whole year is not assessed by real-time operation data, as the case was for October 2022, is because some of the data were unavailable and unreliable for certain months. Therefore, annual estimation of energy efficiency and CO_2 emissions are performed using extrapolation of the October 2022 sailings.

During October 2022, the total of 11 voyages were recorded along with the distances travelled, transit and port calls periods, and respective draughts. In that month, the vessel sailed to 10 ports on a Danube between Belgrade (Serbia) and Svishtov (Bulgaria). October 2022 sailings are divided into 9 sectors, as in Fig. 2. Sectors' average water depths and current speeds are given in Fig. 3.

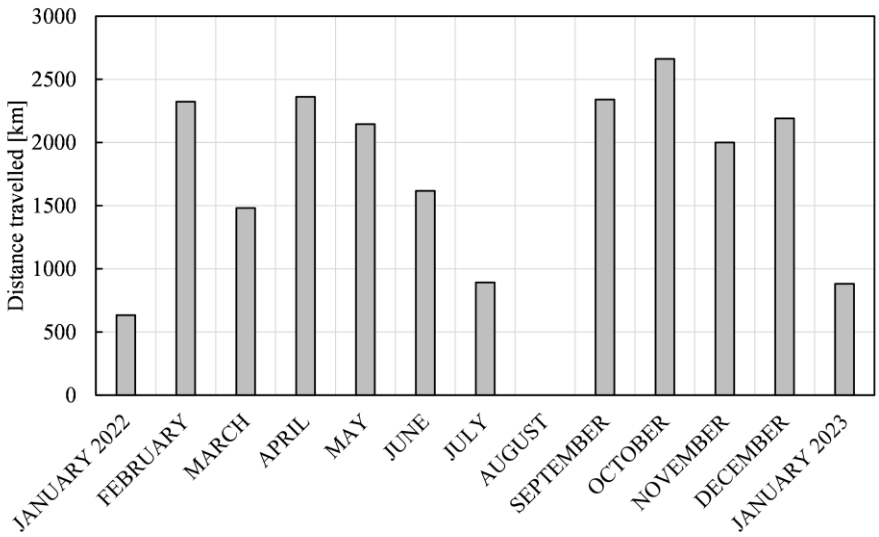

Fig. 1 Distance covered by the vessel navigation for each month during the year

Fig. 2 October 2022 route: map

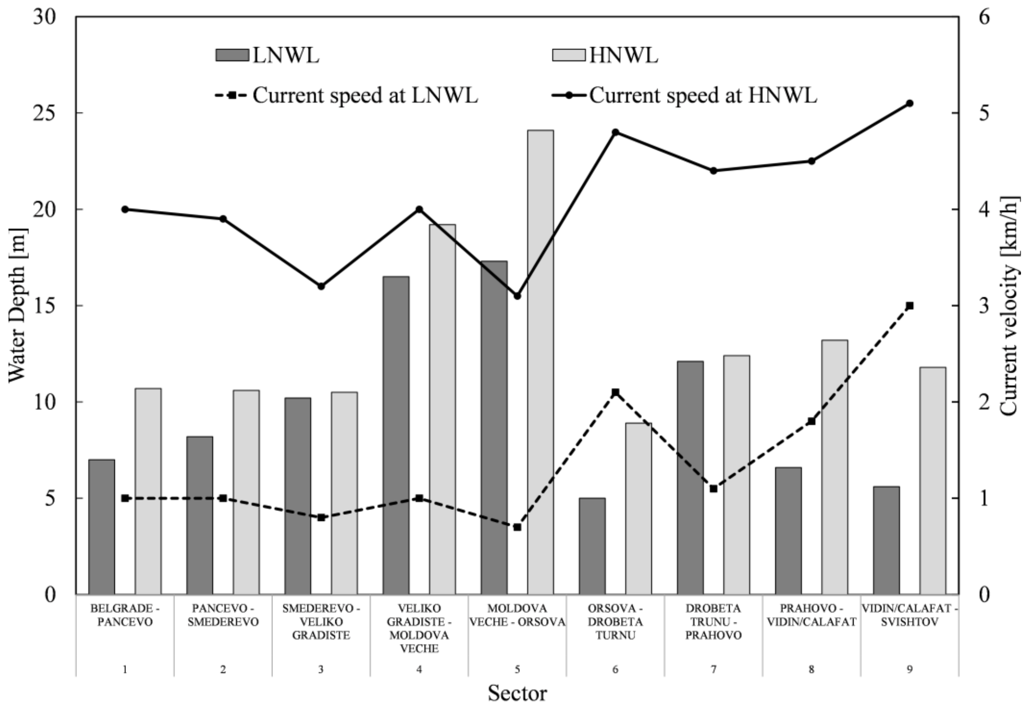

Fig. 3 October 2022 route: water depths and current speeds

Additionally, width of the river for each location is extracted from the documents in [29], which provides a maximum fairway width that is guaranteed by the Danube Commission, throughout the entire year. Based on service draught and available vessel documentation, specifically Trim and Stability Booklet, the displacement and the deadweight are determined. The average sailing speed (speed over ground - SOG) for each voyage was calculated by dividing the distance travelled between the starting and ending destination by the time obtained from subtracting the duration spent in port from the total duration of a certain route. Finally, voyage data for October 2022 navigation are presented in Table 1.

Table 1 Voyages data for October 2022

Voyage no. and port calls	Distance [km]	Draught [m]	DWT [t]	Duration [h]	Speed over ground (SOG) [km/h]
1. Veliko Gradište - Belgrade	108	2.4	1548.5	57.81	1.87
2. Belgrade - Pančevo	15	2.4	1548.5	0.80	18.75
3. Pančevo - Drobeta Turnu Severin	223	2.4	1548.5	10.98	20.30
4. Drobeta Turnu Severin - Svishtov	372	1.7	851.0	29.68	12.53
5. Svishtov – Veliko Gradište	502	2.5	1650.1	88.28	5.69
6. Veliko Gradište - Belgrade	108	2.5	1650.1	11.03	9.79
7. Belgrade	105	2.5	1650.1	92.70	1.13
8. Belgrade - Svishtov	610	1.7	851.0	36.28	16.81
9. Svishtov	9	1.7	851.0	9.33	0.96
10. Svishtov – Veliko Gradište	502	2.2	1346.9	87.03	5.77
11. Veliko Gradište - Belgrade	108	2.2	1346.9	7.33	14.73

Furthermore, the following matrix is created to represent the operation of the vessel during the October 2022, see Fig. 4. During voyages 7 and 9 (crossed cells), the vessel sailed within the area of the port or city. The vessel deadweight varied between 851 t and 1650.1 t.

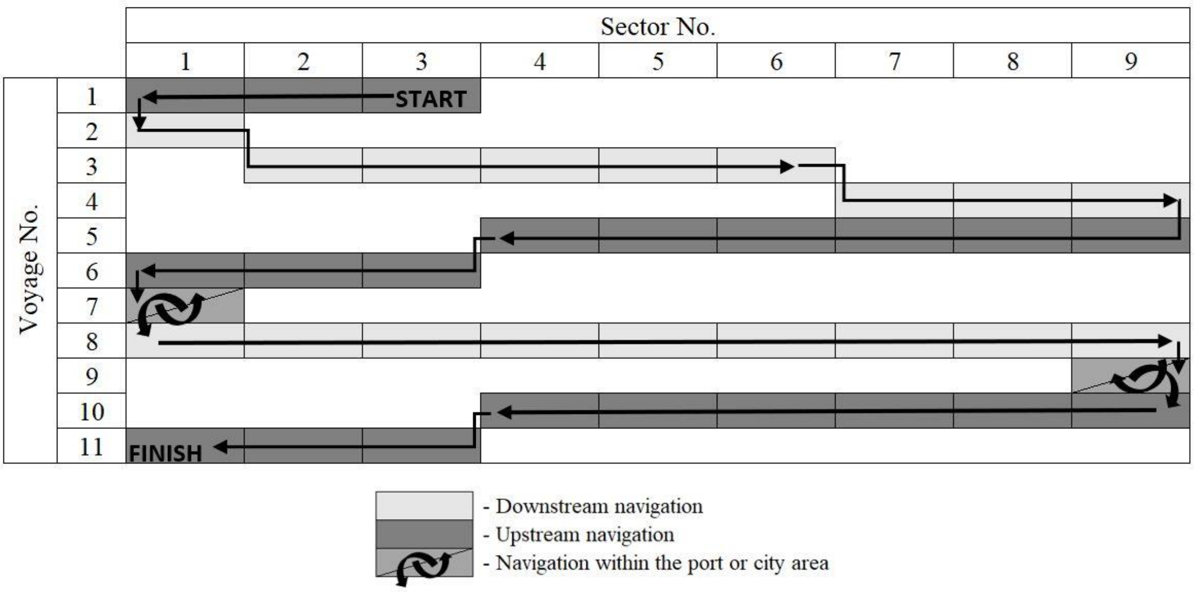

Fig. 4 October 2022 navigation matrix

2.2 Energy efficiency design indices

Energy efficiency design indices are evaluated using two methods proposed so far delivered for European IWV. The first one is called modified energy efficiency design index (EEDI*) [20, 30], and the second one is delivered by DST ($EEDI_{IWV}$) [21]. Both are similar to IMO's EEDI method, so that an attained level of energy efficiency has to be lower than required level of energy efficiency, in order for the vessel to satisfy criteria. The summary of calculation procedures for both methods is shown in Table 2. Their detailed comparison, advantages and disadvantages are comprehensively assessed in [22].

Table 2 Energy efficiency design index proposals for IWV

Index	EEDI*	$EEDI_{IWV}$
Equations	Attained EEDI: $EEDI^*=P_{Bref} \cdot SFC \cdot CF / (m_{DWT} \cdot V)$ Required EEDI: $EEDI^*_{Req}=a \cdot m_{DWT}{}^{c}$ For deep water: $a = 0.39554 \cdot V^2 - 1.27833 \cdot V + 111.69043$ $c = -0.00114 \cdot V^2 - 0.05177 \cdot V + 0.70843$ For Shallow water (h < 5 m): $a = 93.712 \cdot F_{nh}^{-3} - 516.38 \cdot F_{nh}^{-2} + 886.54 \cdot F_{nh}^{-1} - 414.86$ $c = -0.4181 \cdot F_{nh}^{-3} + 2.5716 \cdot F_{nh}^{-2} - 5.2767 \cdot F_{nh}^{-1} + 3.3485$	Attained EEDI: For deep water: $P_D=\alpha_1 \cdot m_{DWT}$ P_D to be measured, V_s to calculate $EEDI_{IWV}$ $EEDI_{IWV} = CF \cdot SFC \cdot P_D /(V_s \cdot m_{DWT})$ For shallow water (h < 7.5 m): $P_D=(\alpha_6+\beta_4 \cdot exp(-\gamma_4 \cdot B)-\delta_2 \cdot exp(h/-_1)) \cdot m_{DWT}$ P_D to be measured, Vs to calculate $EEDI_{IWV}=CF \cdot SFC \cdot PD /(Vs \cdot m_{DWT})$ Required EEDI: For deep water: $EEDI_{Req}= \alpha_4 + \beta_2 \cdot \exp(m_{DWT}/- \gamma_2) + \upsilon_1 \cdot \exp(m_{DWT}/-\delta_1)$ For shallow water (h < 7.5 m):: $EEDI_{Req} = (\alpha_7 + \beta_5 \cdot V_c + \gamma_5 \cdot V_c^2)+(\delta_3+ \varepsilon_2 \cdot V_c - \zeta_1 \cdot V_c^2 + \eta_1 \cdot V_c^3) \cdot \exp(m_{DWT}/- \theta_1)$ Coefficients are given in [22].
Constraints	10 km/h ≤ V ≤ 22 km/h 0.4 ≤ F_{nh} ≤ 0.65 100 t ≤ m_{DWT} ≤ 3000 t	For deep water: T = 1.5D; T =2.0-3.2 m. For shallow water (h < 7.5 m): T = 1.5D; h = 3.5-7.5 m; T = 2-2.8 m; L = 40-135 m; B = 5-17 m; m_{DWT} = 250-6000 t; Vc = 2-8 km/h; min(h/T) = 1.4.
Notes	$EEDI^*$ – modified energy efficiency design index [gCO_2/gFuel]; P_{Bref} – Reference engine power for V [kW]; SFC – Specific fuel consumption [g/kWh]; CF – carbon emission factor, 3.206 [gCO_2/gFuel]; m_{DWT} – mass of deadweight [t]; V – actual vessel speed through water (not on 75% of MCR like in IMO's EEDI) [km/h].	$EEDI_{IWV}$ – energy efficiency design index [gCO_2/tkm]; D – propeller diameter [m]; B – vessel breadth [m]; h – river depth [m]; SFC – specific fuel consumption [g/kWh]; CF – carbon emission factor, 3.206 [gCO_2/gFuel]; m_{DWT} – mass of deadweight [t]; P_D – delivered power [kW].

2.3 Energy efficiency in operation

In order to evaluate energy efficiency of the vessel in operation, an energy efficiency in operation (EEO) index is introduced and calculated. EEO differs from EEOI, since the latter one is delivered by IMO as voluntary tool for sea-going ships and considers already established procedures for sea-going ships, see [5]. On the other hand, EEO takes into account diversified operation of the IWV with respect to shallow water and current speed, which is not considered within IMO's energy efficiency indices. Therefore, EEO is calculated using operational profile inputs (from sect. 2.1), for the specified vessel, into two proposed methods elaborated in sect. 2.2: EEDI* and $EEDI_{IWV}$, see equation (1).

$$EEO_1 = EEDI^* \qquad EEO_2 = EEDI_{IWV}. \tag{1}$$

For the purpose of the analysis, the following assumptions are made:

- required engine power is calculated as ratio of the delivered power and shaft efficiency and taken to be 0.98,
- delivered power is available based on real time measurements during sailings at different draughts,
- the specific fuel oil consumption used in this study is assumed to be 210 g/kWh, and it was obtained as an average value from both methods (the method [20] proposes 200 g/kWh and the method from [21] proposes 220 g/kWh),
- carbon emission factor for diesel fuel is 3.206 g CO_2/g fuel,
- calculation is carried out for both cases of river depth (the lowest and the highest level) in order to obtain the range of CO_2 emissions since there were no available data on water depth during voyages.

3. Case study

The case study is represented by the typical self-propelled cargo vessel with general arrangement and particulars as shown in Fig. 5 and Table 3, respectively. The vessel is designed to carry bulk cargo and additionally, if necessary, push other vessels (barges).

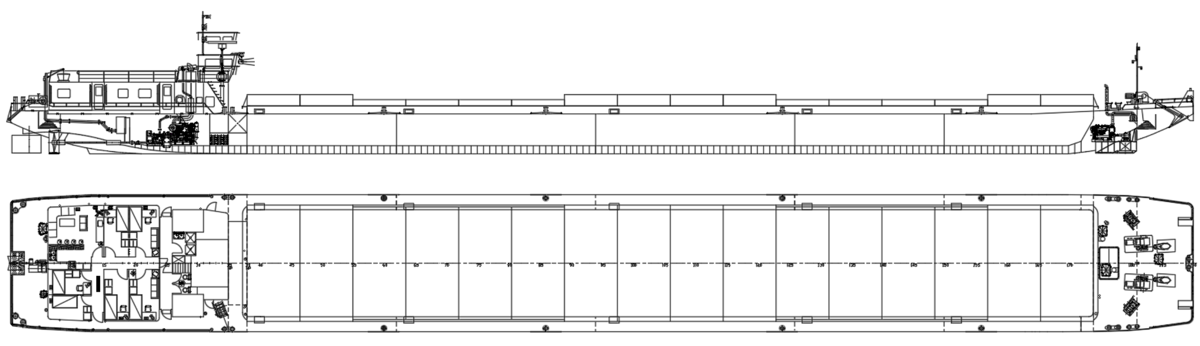

Fig. 5 General arrangement of the vessel

Table 3 Vessel particulars

Length	95 m
Width	11 m
Height	3.2 m
Draught	2.7 m
Deadweight mass	1850 t
Lightweight mass	637 t
Engine power	2 x 638 kW
Propeller diameter	2 x 1.6 m

4. Results and discussion

Results are evaluated for October 2022 navigation for the lowest (LNWL) and the highest (HNWL) water depths, as a function of speed through water (STW). Each of the 11 voyages are divided into the nine sectoral voyages (9 in total, see Fig. 4.) for which an energy efficiency is assessed. During each of the sector passings, the vessel had the corresponding: draught (ranging between 1.7 m and 2.4 m), deadweight, STW, distance covered. EEO is calculated according to equation (1). In addition, EEO results are compared to the requirements of the energy efficiency design indices, given by two methods (EEDI* and $EEDI_{IWV}$). EEDI* requirement is labelled here as $EEOI_{1,\,req}$. On the following diagrams, this requirement is represented by the curve separating the right area (coloured in grey, on the right side of diagrams), meaning that the vessel has unsatisfactory energy efficiency; and the left side, in which the vessel has met the requirement. Furthermore, $EEDI_{IWV}$ method can have multiple requirements: $EEOI_{2,\,req\ i}$ - requirement for the sector i; and (or) $EEOI_{2,\,req\ j,\,k,\,l}$ – requirement for the sectors j, k, l. The area above these lines represents the energy efficiency not satisfied by the vessel. $EEDI_{IWV}$ can have multiple criteria, compared to EEDI* single curve requirement. This is due to fact that $EEDI_{IWV}$ has different definition of the shallow water. Water is considered to be shallow if the depth is less than 5 m according to EEDI* method; and less than 7.5 m, according to the $EEDI_{IWV}$ method. In all sectors considered (see Fig. 3), the actual water depth was recorded to be above 5 m, meaning that it was defined as deep water by EEDI*, and single corresponding calculation procedure is used (see Table 2). Instead, although being above 5 m in depth, in some sectors, the water depth was recorded to be lower or higher than 7.5 m, so that the different requirement formula is used when $EEDI_{IWV}$ method was applied. Thus, energy efficiency requirements are different by sector because they depend on navigation conditions, as shown in formulas given in Table 2. Therefore, EEO are given as averaged values per voyage. Diagrams of energy efficiency for each of 11 voyages, for LNWL and HNWL are presented in Fig. 6 and Fig. 7, respectively.

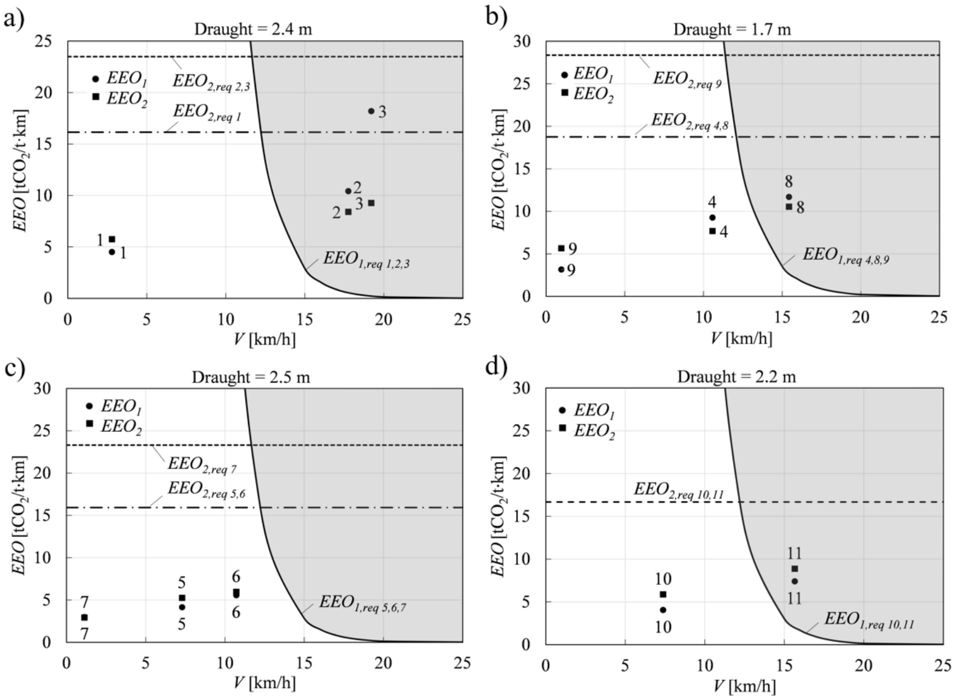

Fig. 6 Energy efficiency for October 2022 navigation for LNWL, for voyages no.: a) 1,2,3, b) 4,8,9, c) 5,6,7, d) 10, 11

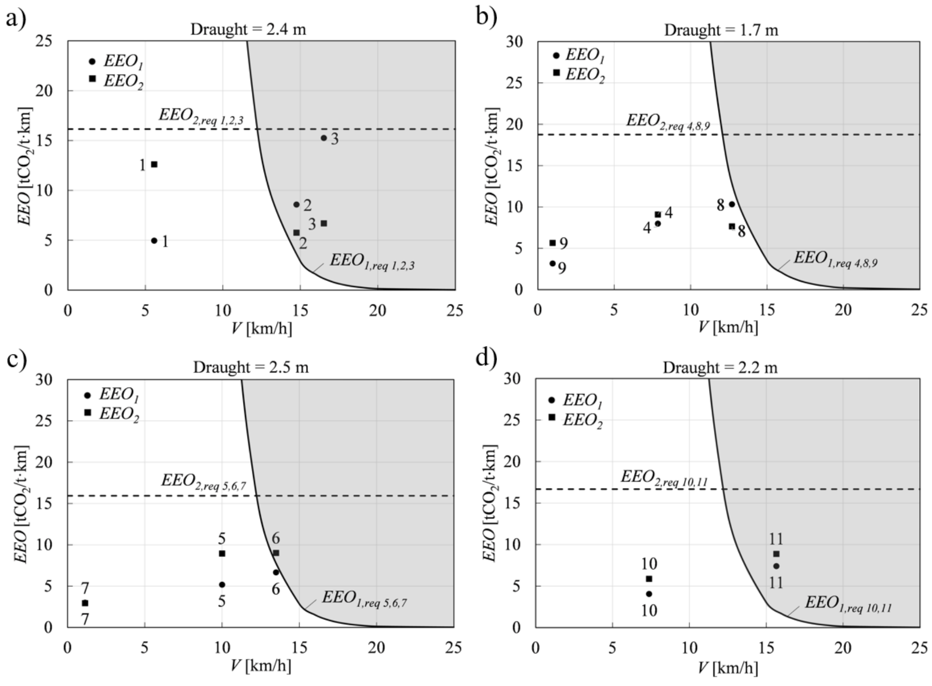

Fig. 7 Energy efficiency for October 2022 navigation for HNWL, for voyages no.: a) 1,2,3, b) 4,8,9, c) 5,6,7, d) 10, 11

When sailing at LNWL, the vessel meets $EEDI_{IWV}$ requirements, while EEDI* is not satisfied for voyages 2, 3, 8 and 11. Based on the EEDI* requirement curve, the vessel sailing above 13-15 km/h (almost for all deadweights) will always be in prohibited zone, independent of the draught, meaning that the vessel will not be an energy efficient for those speeds. Therefore, decreasing the speed (and engine power) can result in a more energy efficient performance, as such is the case for sea-going ship as well, see also [8]. In contrast, there is no speed limit for the $EEDI_{IWV}$ approach, with respect to deadweight. Note that typical speed of IWV on Danube River is between 12 and 20 km/h, depending on various factors such as water levels, current speeds, vessel type and traffic density. In case of the scenario in which the vessel is sailing at HNWL, EEDI* criterion is not satisfied for voyages no. 2, 3 and 11 (voyage 6 is at the limit). Voyage no. 8, which did not meet the requirement at LNWL, is now energy efficient. This is due to fact that, according to this method, the definition of the shallow water is different, and hence, the requirement criterion, implying that the vessel is now sailing in deep water and therefore, more efficient. Unlike to results from Fig. 6, $EEDI_{IWV}$ method has only one requirement at HNWL, as vessel operates in high water conditions. Methods are insensitive to the deadweight change, which is a disadvantage and not representing the realistic navigation conditions. Also, the definition of the shallow water plays a significant role in final results, as the different calculation procedures for requirement curves are included.

Furthermore, based on previous results, the total amount of CO_2 emissions released in October 2022 is calculated by multiplying the EEO with the distance travelled and DWT, see Table 4.

Table 4 Total amount of CO_2 emissions for October 2022

	At LNWL		At HNWL	
	Based on EEO_1	Based on EEO_2	Based on EEO_1	Based on EEO_2
Total amount of CO_2 emitted [t]	24.6	22.7	24.9	29.9

According to EEO_1, the total emitted CO_2 in October 2022 is between 24.6 t and 24.9 t, while considering EEO_2, the range is wider: 22.7 t – 29.9 t. The result of the EEO_2 at HNWL is a bit larger than other three, as $EEDI_{IWV}$ method has different calculation procedure and requirement for the deep-water case. Authors could not perform the same analysis for the whole year as for October 2022, due to the time-consuming acquirement of the unsystematically available data for remaining months. In addition, there were periods in which the vessel was completely unemployed, as in August. Thus, the October 2022 emissions were scaled up to the whole year: the annual CO_2 emissions are calculated according to the deadweight and distance travelled for other months during sailing, as shown in Table 5.

For the whole year of sailing (extrapolated from October 2022 results and including distance travelled and deadweight for remaining months), the total released CO_2 is 197-199 t according to EEO_1 and 182-189 t according to EEO_2. Here, the assumption is made that the vessel performed through the whole year as in its most employed month. Moreover, assuming that the vessel had sailed during all months of the year like in October 2022 (now, not taking into account actual deadweight and distance travelled of remaining months), the amount of CO_2 emissions is calculated to be in between 244-329 t (excluding August, in which the vessel was idle). Note that IWV compete with rail and road cargo for freight transport over land. For the sake of comparison, a single heavy-duty truck (which carries 30 t) emits around 36 tons of CO_2 annually, when data from [31] are used. This means that, annually, 5-6 of them would emit the same amount of CO_2 as the selected vessel.

Table 5 Total CO_2 emissions for the whole year

Month	Distance travelled [km]	DWT [t]	Total amount of CO_2 emitted [t]			
			At LNWL		At HNWL	
			Based on EEO_1	Based on EEO_2	Based on EEO_1	Based on EEO_2
January 2022	633	1003.6	4.3	4.0	4.4	4.0
February	2323	1571.8	25.0	23.0	25.3	23.0
March	1482	1462.3	14.8	13.7	15.0	13.7
April	2362	1198.8	19.4	17.9	19.6	17.9
May	2145	1334.1	19.6	18.0	19.9	18.0
June	1618	1605.3	17.8	16.4	18.0	16.4
July	892	1130.7	6.9	6.4	7.0	6.4
August	0	0	0	0	0	0
September	2341	1127.9	18.0	16.7	18.3	16.7
October	2662	1349.3	24.6	22.7	24.9	29.9
November	2000	1185.9	16.2	15.0	16.2	15.0
December	2191	1387.3	20.8	19.2	20.8	19.2
January 2023	882	1650.1	9.9	9.2	9.9	9.2
Total	**21531**	**/**	**197**	**182**	**199**	**189**

Moreover, additional analyses are performed to identify sectoral EEO. Thus, critical voyages from Fig. 6 and Fig. 7 are extracted, in which energy efficiency requirement was not satisfied. EEDI* requirement was chosen for further analysis as this is more restrictive method. $EEDI_{IWV}$ criteria was passed in previous analyses. In the next step, voyages are separated into the sectoral voyages. They include four voyages performed during the LNWL and three voyages during the HNWL conditions. During the LNWL, voyages included are: no. 2 (sector: 1), no. 3 (sectors: 2-6), no. 8 (sectors: 1-9) and no. 11 (sector: 1-3). During the HNWL conditions identified are critical voyages: no 2 (sector: 1), 3 (sector: 2-6) and no. 11 (sector: 1-3). Their EEO results are presented in Fig 8. Label "i/j" corresponds to the voyage no. i, on a sector no. j. In all voyages with criterion unsatisfied, their corresponding energy efficiency by each of the sector also proved to be unsatisfactory by the requirement. Results shows that energy efficiency of the vessel depends whether the navigation is performed during upstream or downstream navigation. Voyage no. 2 and 3 was carried out while downstream and was more efficient in deep water. In contrast, voyage no. 11 was performed upstream and thus, is less efficient. It is due to fact that diagrams are given as a function of STW, not SOG speeds. For the same SOG, the vessel had to use more power upstream because of the increased current speed. Therefore, energy efficiency of the vessel depends on the downstream or upstream sailings. Note that $EEDI_{IWV}$ method does not consider the direction of the river flow.

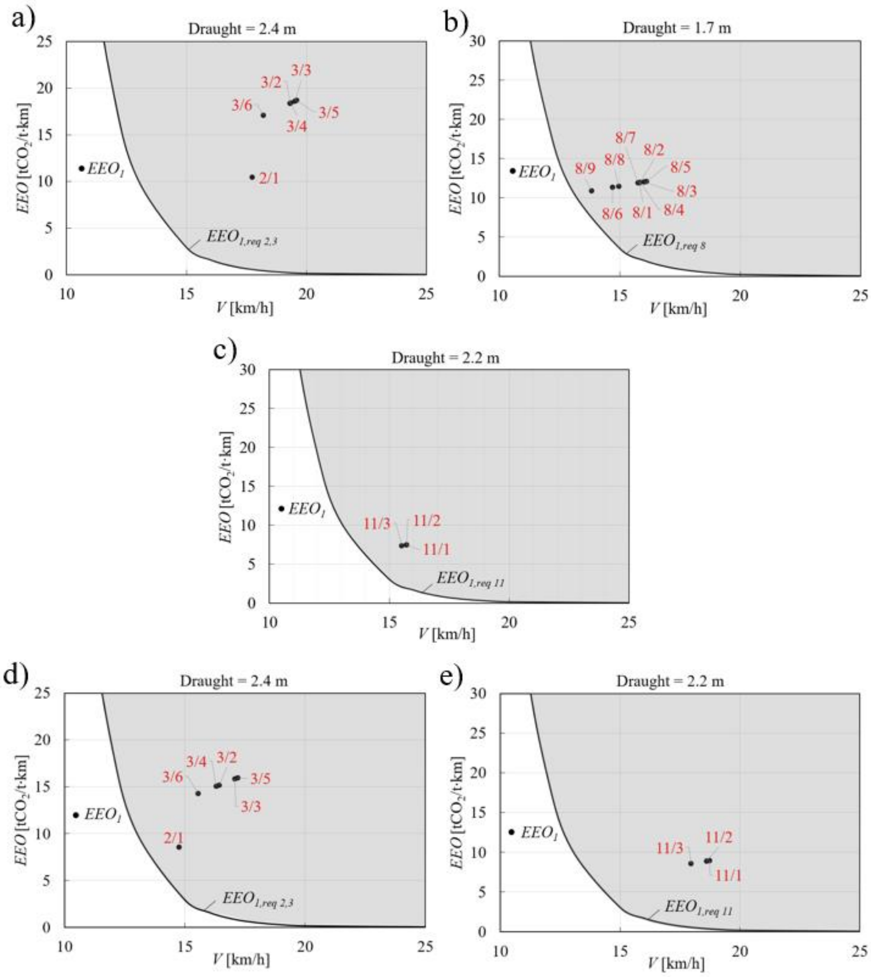

Fig. 8 Energy efficiency for October 2022 navigation at LNWL (a, b, c) and at HNWL (d, e), for voyages with respect to sector

In all sectors, speed had to be decreased (i.e., perform slow steaming) for the vessel to meet the energy efficiency criterion. Therefore, calculated are necessary sectoral speed over ground reductions by voyage. They are given in the following Table 6. At LNWL, the average speed reduction by sectors is in between 4.8% and 26%. In case of HNWL sailing, the speed reduction varies between 14.3% and 25.8%.

If the speed was reduced, the sailing time would be extended, so the additional time that the vessel spent in navigation has also been calculated on a monthly basis, and then the estimated extension of time has been evaluated on an annual basis. Results are shown in the Table 7.

Table 6 Reduction of the speed over ground in km/h and percentages

		Sectors								
		1	2	3	4	5	6	7	8	9
Voyage no. at LNWL	2	4.25 (22.6%)								
	3		6.6 (32.5%)	6.8 (33.5%)	6.7 (33.0%)	6.9 (34.0%)	5.5 (27.1%)			
	8	2.71 (16.1%)	2.71 (16.1%)	2.91 (17.3%)	2.81 (16.7%)	3.01 (17.9%)	1.61 (9.6%)	2.71 (16.1%)	1.91 (11.4%)	0.81 (4.8%)
	11	1.93 (13.1%)	1.93 (13.1%)	1.73 (11.8%)						
Average by sector at LNWL		17.3%	20.6%	20.9%	24.9%	26%	18.4%	16.1%	11.4%	4.8%
Voyage no. at HNWL	2	1.25 (6.6%)								
	3		3.8 (18.7%)	4.4 (21.7%)	3.6 (17.8%)	4.5 (22.2%)	2.9 (14.3%)			
	11	4.83 (32.8%)	4.83 (32.8%)	4.13 (28.1%)						
Average by sector at HNWL		19.7%	25.8%	24.9%	17.8%	22.2%	14.3%			

Table 7 Additional time needed for the compliance with the EEDI* requirements by means of slow steaming

Additional time for navigation [h]		
Month	At LNWL	At HNWL
January 2022	2.6	1.5
February	9.4	5.3
March	6.0	3.4
April	9.5	5.4
May	8.7	4.9
June	6.5	3.7
July	3.6	2.0
August	0.0	0.0
September	9.4	5.4
October	10.7	6.1
November	8.1	4.6
December	8.8	5.0
January 2023	3.6	2.0
Total	**87**	**49**

If the vessel had slowed down at certain sectors in order to meet the criterion, it would have sailed an additional 10.7 h or 6.1 h depending on the water depth, during October 2022. On an annual basis, the estimated extension of travel time would be 87 h and 49 h at LNWL and HNWL, respectively. This appears as negligible additional sailing when considering the total number of days vessel spent in transit. However, one should note that this is also governed by the fact that the vessel was already slow and did not navigate extensively, which is not accounted within the available method and therefore, can be improved.

This study represents an initial step towards the development of energy efficiency assessments that take into account the operational data and actual fairway constraint changes for IWV. By considering operational data, this research provides a more explicit evaluation of the energy performance for typical IWV, which is still unaddressed in the literature. Hence, these findings could set a benchmark for the actual vessel energy efficiency and could pave the way for the development of future mandatory regulations for improving the energy efficiency of IWV and reducing their environmental impact.

5. Conclusions

Energy efficiency regulations, corresponding mandatory indicators and requirements do not exist in inland navigation. Moreover, literature data is almost negligible compared to the sea-going ships. This is disturbing considering that IWV represents the large sector responsible for harmful emissions released while navigating through the urban areas. Compared to the sea-going ships which have no competition in international deep-sea freight transport, IWV transport cargo “over land”, while competing directly with rail and road modes. IWV navigation is diverse, and their energy efficiency, unlike for sea-going ships, depends on additional parameters, such as water depth, current speeds, fairway constraints, etc. Therefore, this paper aims to fill the gap and deliver one of the first attempts to quantify the energy efficiency of the vessel in actual navigation using real-time data. Moreover, it aims to provide an analysis of energy efficiency in operation (EEO) of the typical cargo vessel navigating on Danube. EEO is evaluated based on operational data for a most employed month of navigation during the year, between January 2022 and January 2023. Only two proposed methods are used to calculate and assess EEO for different voyages during the designated period of one month, and annually. These methods are only available for EU waterways, they are published, but still did not achieve mandatory status.

Results showed that for the same voyage, EEO and CO_2 emitted significantly differs with respect to sector of navigation. That is because each of the sector has different fairway constraints, largely depending on the level of water depth. In general, low water depth generally decreases the energy efficiency of the vessel. The total CO_2 emitted is delivered and is in between 22.7 and 29.9 tons for the most employed month of sailing and between 182 and 199 tons, annually, if the vessel has sailed according to the designated distance travelled and deadweights for remaining months. The actual speed reduction by sectors, necessary for the requirement compliance, is estimated to be 4.8%-26% for sailing at LNWL and 14.3%-26% when sailing at HNWL.

By introducing regulations aimed at limiting CO_2 emissions from vessels and reducing the speed of navigation, energy efficiency could be improved to certain extent, and the extension of the duration of a voyage would be only slightly longer, as assessed in the paper. This can easily be achieved by implementing cruise control on vessels, which can also be equipped with diagrams like those presented in this study, in which it is possible to oversee in real-time whether the vessel satisfied the requirements. Further research should conduct a more detailed investigation for other months, as well as research for other vessels and zone of navigations. Parallel efforts should be made to harmonize the methods for determining the energy efficiency of IWV, as they have not yet officially entered into force. Furthermore, due to diverse operation of the IWV, only real-time measurement during the navigation thought the different conditions would represent the actual energy efficiency of the vessel, as the energy efficiency of the IWV vastly depends on the river configuration, water depths, precipitation, locks dimensions, river curvature, the existence of the hydropower plants, speed of the vessel, fuel oil consumption, etc.

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ABBREVIATIONS

CCNR	Central Commission for the Navigation of the Rhine
CII	Carbon Intensity Indicator
DCS	Data Collection System
DST	Duisburg’s Development Centre for Ship Technology and Transport Systems (*DST Entwicklungszentrum für Schiffstechnik und Transportsysteme*)
DWT	Deadweight
EEDI	Energy Efficiency Design Index
EEDI*	Modified Energy Efficiency Design Index (for IWV)
$EEDI_{IWV}$	Energy Efficiency Design Index (for IWV)
EEO	Energy Efficiency in Operation
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EU	European Union
GHG	Greenhouse Gas
GT	Gross Tonnage
HNWL	Highest Navigable Water Level
IMO	International Maritime Organization
IWV	Inland waterway Vessel
LNWL	Lowest Navigable Water Level
SOG	Speed over ground
STW	Speed through water

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Milan Kalajdžić
University of Belgrade, Faculty of Mechanical Engineering, Department of Naval Architecture, Kraljice Marije 16, 11120 Belgrade 35, Serbia, mdkalajdzic@mas.bg.ac.rs
Matija Vasilev
Ocean Pro Marine Engineers LTD, 8 Stasnoja Glavaša, 11000 Belgrade, Serbia
Nikola Momčilović
University of Belgrade, Faculty of Mechanical Engineering, Department of Naval Architecture, Kraljice Marije 16, 11120 Belgrade 35, Serbia