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EVALUATING AN INLAND WATERWAY CARGO VESSEL'S ENERGY EFFICIENCY INDICES

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ABSTRACT

Although the International Maritime Organization (IMO) introduced the energy efficiency requirements for ships more than a decade ago, to date, inland navigation has not been affected by corresponding regulations at all. Therefore, inland waterway vessels are left with no mandatory requirements that could push their technology into more energy efficient design. Fortunately, there are certain pioneering attempts to define energy efficiency criteria for inland vessels. This paper tries to gather and provide a review of such methods. Moreover, a typical Danube cargo inland vessel's data are used to evaluate their current energy efficiency levels with respect to provisional criteria. Consequently, two methods are found and used here. They are both based on IMO's energy efficiency concept but modified for the inland waterway vessels. The methods delivered a significant difference in applicability and were difficult to compare. Moreover, shallow and deep-water effects are explored in the same regard but provided unsound conclusions. The final results displayed discrepancies in energy efficiency levels for the same vessels and so the methodology should be improved and harmonised, if it is to be introduced as mandatory for inland waterway vessels. The analysis provided a glimpse into the current condition of the traditional design of the Danube inland fleet, with respect to the emerging energy efficiency policies.

Keywords: Inland vessels, Energy efficiency, Energy efficiency of inland vessels, EEXI, EEDI

INTRODUCTION

The reduction criteria for greenhouse gas emissions (GHG), issued by the International Maritime Organization (IMO), have been mandatory for newly built sea-going ships over 400 gross tonnage (GT) since 2013. In the case of existing ships, the corresponding requirements are set to start from 2023. These regulations, in the form of energy efficiency indices, are being implemented as a short-term measure and are intended to be strengthened over time to achieve the final long-term goal reductions. Therefore, the IMO introduced a set of energy efficiency indices through its Marine Environment Protection Committee (MEPC). The indices were intended to measure a ship's energy efficiency level. The first one, energy efficiency design index (*EEDI*), was first introduced in 2011 and applied two years later for new ships [1], while incrementally strengthening the criteria every five years. The *EEDI* value (attained *EEDI*) corresponds to the grams of carbon dioxide (CO_2) emissions per ship's capacity-mile and is to be calculated for each ship. Attained *EEDI* must be lower than the required *EEDI*, which is the criterion also imposed by IMO. Furthermore, following the Paris Agreement and the global need for GHG emission reduction, IMO presented a strategy for shipping. In general, it can be summarised as being: to strengthen requirements for *EEDI* over the years, to reduce the carbon intensity of ships (CO_2 per transport work to at least 40% by 2030, reaching a 70% reduction by 2050) and to reduce GHG emissions to at least 50% by 2050, when compared to 2008 levels [2]. Moreover, IMO addressed the efficiency of existing ships in the same manner as in the case of EEDI, i.e., by introducing EEXI, which stands for 'energy efficiency of existing ships'. This requirement is set to start applying from 2023 [3].

In the meantime, ships are mostly fighting against the indices' criteria by slow steaming, while technological improvements like energy saving devices (ESD) and alternative fuels (and optimisation of the hull) still need some time to become fully applicable. Nevertheless, some authors have investigated the relation between fleets of existing ships and emerging indices: in cases of fleets of multi-purpose ships [4] and in cases of various ship classes [5]. Others have even recognised the 'energy efficiency gap' [6], labelling the industry's reluctance to address the use of novel technologies in order to reduce emissions.

Contrary to sea-going shipping, inland waterway vessel (IWV) regulations are much less unified. Depending on their navigation and cargo, IWV rely on various interconnected national, regional and international regulations. Unfortunately, these are not fully consolidated. However, the UN and EU are, indeed, trying to harmonise regulations on an international level [7, 8]. The EU inland fleet consists of 10,000 vessels registered in countries interfacing the Rhine, while an additional 3500 and 2300 vessels are registered along the Danube and in other EU countries, respectively, according to [9]. However, there are innovations that include energy efficient inland vessel designs. Reduced fuel consumption, air pollution and improved overall efficiency (considering specific waterway conditions) were investigated for merchant river vessels in [10]. Moreover, a high energy efficiency inland ferry concept was developed in [11], using hybrid propulsion. Similarly, the research in [12] explored hybrid propulsion as well, in addition to potential hull shape modification, to design a more energy efficient small inland passenger vessel.

Still, no mandatory requirements are available for the energy efficiency of IWV in any form. An explanation could be found in the much lower total GHG emissions of IWV transport when compared to road transport (in EU member states) and a conservative IWV industry. Yet industries that are not pursuing decarbonisation politics are risking exposure to social discontent.

Therefore, this paper aims to present a review of proposed and provisional methods for the calculation of energy efficiency indices for IWV. Furthermore, energy efficiency indices are calculated for typical Danube vessels. The results are expected to provide a perspective on current IWV designs regarding the initial energy efficiency criteria.

ENERGY EFFICIENCY INDICES FOR INLAND WATERWAY VESSELS

Although no energy efficiency regulations have been developed for IWV, overall efficiency indices are available in a non-regulatory form. They are mostly related to the hydrodynamic performance of the vessels and transport efficiency, but not directly to the energy efficiency from an environmental point of view, as in the case of *EEDI* or *EEXI*. Proposed energy efficiency indices, in particular, (explored for IWV and EU waterways) have already been systematically presented in [13], while the original research was delivered in [14, 15]. There are very few studies available regarding EU waterways but there is a study on this topic for waterways outside the EU, see [16, 17].

Proposed energy efficiency methods are based on the *EEDI* concept. Accordingly, the calculated or estimated so-called 'attained *EEDI*' should be lower than the required *EEDI* value. When evaluating energy efficiency performance with respect to the IMO's *EEDI* approach, it should be considered that IWV usually have larger engines than they need for the designed speed. This is because of the additional operations of IWV, compared to sea-going vessels. For instance, IWV are intended to push barges and to be coupled with other vessels. Therefore, using just the IMO procedure for IWV would not be suitable, since the *EEDI* formula for sea-going ships considers 75% of the engine power in still water. Moreover, inland vessel operations heavily depend on navigation conditions. This accounts for large variations of the draught between deep and shallow-draught vessels. The draught governs the propeller diameter and, thus, the installed power, which directly influences energy efficiency index. In addition, it should be noted that vessels use less power when operating downstream, compared to upstream. Consequently, IWV energy efficiency indices cannot just be transferred from the maritime sector.

MODIFIED EEDI

One of the first attempts to define the energy efficiency of IWV can be found in [13]. The method is based on IMO's *EEDI* approach and labeled as modified *EEDI* or *EEDI**. It was developed at the Department of Naval Architecture (University of Belgrade). The method presents a procedure for the calculation of attained *EEDI** and required *EEDI**. It can be used for existing vessels as well. The proposal presents the benchmark study, that can be comparable to phase 0 of the EEDI requirement, delivered for sea-going ships built after 2013, see [1]. The summary of the method, referred to here as Method 1, is presented in Table 1.

DST EEDI

DST (Development Centre for Ship Technology and Transport Systems), a Duisburg based institute, proposed equations for the assessment of energy efficiency of IWV, see [15]. The method classifies four vessel types: dry cargo/container self-propelled vessels, tankers, pushed convoys and passenger vessels. It also differentiates equations according to the navigation zones. Here, the procedure is given for cargo vessels carrying dry bulk or containers, considering the navigation in deep and shallow water. The method is presented in Table 2 and referred to as Method 2. Deep water corresponds to a water depth of 7.5 m

Tab. 1. Method 1

Indices	Attained *EEDI**	Required *EEDI**
Equation	$EEDI^* = P_{Bref} \cdot SFC \cdot CF / (m_{DWT} \cdot V)$	$EEDI^*_{Req} = a \cdot m_{DWT}^{c}$
Ranges	$10\ km/h \le V \le 22\ km/h$; $0.4 \le Fnh \le 0.65$; $100\ t \le m_{DWT} \le 3000\ t$	
Explanations and coefficients	$EEDI^*$ – Modified energy efficiency design index [gCO_2/gFuel]; P_{Bref} – Reference engine power for achieving V [kW]; *SFC* – Specific fuel consumption, assumed 200 [g/kWh]; *CF* – carbon emission factor, 3.206 [gCO_2/gFuel]; m_{DWT} – mass of deadweight [t]; V – actual vessel speed through water [km/h].	Deep water: $a = 0.39554 \cdot V^2 - 11.27833 \cdot V + 111.69043$ Shallow water: $a = 93.712 \cdot F_{nh}^{-3} - 516.38 \cdot F_{nh}^{-2} + 886.54 \cdot F_{nh}^{-1} - 414.86$ Deep water: $c = -0.00114 \cdot V^2 - 0.05177 \cdot V + 0.70843$ Shallow water: $c = -0.4181 \cdot F_{nh}^{-3} + 2.5716 \cdot F_{nh}^{-2} - 5.2767 \cdot F_{nh}^{-1} + 3.3485$
Notes	- *V* is not governed on 75% of MCR like in IMO's *EEDI* approach, but poses an actual speed with reference to the water; - P_{Bref} is reference power, not based on MCR like in IMO's *EEDI* approach; - *EEDI** is to be assessed for all vessels in the same speed and river constraints (for instance: shallow water) to allow comparison.	- Benchmarking level formula is based on more than 10 year old vessels, but it is proposed that data should be collected from vessels built in the past 10 years; - *a, c* are functions of vessel type and *V* or Froude number F_{nh} in case of shallow water, $h = 5$ m; - The formula is proposed to be strengthened over the years for 10%, 20% and 30% like in the case of IMO's *EEDI*.

Tab. 2. Method 2

<table>
<tr><th>Indices</th><th colspan="5">Attained EEDI ($EEDI_{IWV}$)</th><th colspan="4">Required EEDI ($EEDI_{Req}$)</th></tr>
<tr><td rowspan="2">Equation</td><td colspan="5">Deep water:
$P_D = \alpha_1 \cdot m_{DWT}$
P_D measure, V_s calculate $EEDI_{IWV}$
$EEDI_{IWV} = CF \cdot SFC \cdot P_D / (Vs \cdot m_{DWT})$</td><td colspan="4">Deep water:
$EEDI_{Req} = \alpha_4 + \beta_2 \cdot \exp(m_{DWT}/- \gamma_2) + \upsilon_1 \cdot \exp(m_{DWT}/-\delta_1)$</td></tr>
<tr><td colspan="5">Shallow water:
$P_D = (\alpha_6 + \beta_4 \cdot \exp(-\gamma_4 \cdot B) - \delta_2 \cdot \exp(h/-\varepsilon_1)) \cdot m_{DWT}$
P_D measure, V_s calculate $EEDI_{IWV} EEDI_{IWV} = CF \cdot SFC \cdot P_D /(Vs \cdot m_{DWT})$</td><td colspan="4">Shallow water:
$EEDI_{Req} = (\alpha_7 + \beta_5 \cdot V_c + \gamma_5 \cdot V_c^2) + (\delta_3 + \varepsilon_2 \cdot V_c - \zeta_1 \cdot V_c^2 + \eta_1 \cdot V_c^3) \cdot \exp(m_{DWT}/- \theta_1)$</td></tr>
<tr><td rowspan="2">Ranges</td><td colspan="9">Deep water: $T = 1.5D$; $T = 2.0\text{-}3.2$ m</td></tr>
<tr><td colspan="9">Shallow water: $T = 1.5D$; $h = 3.5\text{-}7.5$ m; $T = 2\text{-}2.8$ m; $L = 40\text{-}135$ m; $B = 5\text{-}17$ m; $m_{DWT} = 250\text{-}6000$ t; $V_c = 2\text{-}8$ km/h; min(h/T) = 1.4</td></tr>
<tr><td rowspan="9">Coefficients</td><td colspan="9">Deep water:</td></tr>
<tr><td>α_1</td><td>α_3</td><td>α_4</td><td>β_1</td><td>β_2</td><td>γ_1</td><td>γ_2</td><td>δ_1</td><td>υ_1</td></tr>
<tr><td>0.262</td><td>0.146</td><td>10</td><td>0.25</td><td>13</td><td>11</td><td>470</td><td>4500</td><td>8</td></tr>
<tr><td colspan="9">Shallow water:</td></tr>
<tr><td>α_6</td><td>α_7</td><td>α_8</td><td>α_9</td><td>β_4</td><td>β_5</td><td>β_7</td><td>β_8</td><td rowspan="6"></td></tr>
<tr><td>0.375</td><td>21</td><td>18</td><td>0.375</td><td>0.0625</td><td>0.7</td><td>0.0625</td><td>2.5</td></tr>
<tr><td>γ_4</td><td>γ_5</td><td>γ_7</td><td>δ_2</td><td>δ_3</td><td>δ_5</td><td>δ_6</td><td>ε_1</td></tr>
<tr><td>0.13</td><td>0.28</td><td>8</td><td>0.5</td><td>11</td><td>0.5</td><td>0.75</td><td>2.8</td></tr>
<tr><td>ε_2</td><td>ε_4</td><td>ε_5</td><td>ζ_1</td><td>ζ_3</td><td>η_1</td><td>η_3</td><td>θ_3</td></tr>
<tr><td></td><td>0.78</td><td>2.8</td><td>0.25</td><td>0.46</td><td>0.375</td><td>0.154</td><td>3100</td><td>800</td></tr>
<tr><td>Explanations</td><td colspan="9">D – propeller diameter [m]; B – vessel breadth [m]; h – river depth [m]; *SFC* – specific fuel consumption, assumed to be 220 [g/kWh]; *CF* – carbon emission factor, 3.206 [gCO_2/gFuel]; *PD* – delivered power [kW]; $EEDI_{IWV}$ – attained (estimated energy efficiency design index [gCO_2/tkm]; $EEDI_{Req}$ – required energy efficiency designed index [gCO_2/tkm].</td></tr>
<tr><td>Notes</td><td colspan="9">For dry bulk and container vessels; For deep water (h>7.5m) and shallow water (zone 3) navigation;
The method is proposed to be strengthened over the years for 15% and 25%.</td></tr>
</table>

and above, while shallow water (which is defined as Zone 3 of the navigation conditions in EU inland waterways) accounts for the lower water depths.

ON MODELS AND THEIR APPLICABILITY

Proposed indices for inland vessels are not (formally speaking) energy efficiency indices for new vessels, as far as they correspond to those considered in IMO regulations for sea-going ships. They are, rather, indices for existing vessels, although they are labelled as *EEDI* here and could be used as such.

In this paper, a database consisting of 44 vessels was taken from the database in Method 1, published in [14] and used as a starting point for the analysis. The database contains hydrodynamic characteristics of self-propelled river cargo vessels obtained during the navigation and in model testing. Firstly, in order to evaluate energy efficiency indices for both methods, it was necessary to estimate the delivered power – speed curve for the vessels. Estimation of the delivered power – speed curve can be performed using the complex mathematical model developed in [14], via an artificial neural network approach. Respective input variables include: waterline length (L_{wl}), breadth (B_{wl}), draught (T), volumetric displacement (∇), ship speed through water (V), hydraulic radius (R_h), waterway breadth (b) and waterway depth (h). The output of the mathematical model is a coefficient of delivered power (CD) which is then used for the calculation of the delivered power according to: $PD = CD \cdot (\rho \cdot g \cdot \nabla \cdot V)$. However, the mathematical model could not be applied for all cases because of the applicability limitations of the methods. Therefore, for the vessels that are 'out' of the limit and, moreover, their power – speed curve is not available as a part of the documentation, new river trials should be performed to obtain such dependency. Nonetheless, input variables for the required index are much less complex to acquire and include: Froude number based on water depth (Fnh) and deadweight (m_{DWT}) for Method 1; and speed of the river (Vc) and deadweight (m_{DWT}) for Method 2.

River speeds considered in the assessments were 2, 4 and 6 km/h, as this range corresponds to the applicability of the methods. The authors did not have all the parameters of the fleet that were required. Therefore, empirical equations given in [14] and recommendations from [18] were used to estimate missing data, which mostly concerned the deadweight values for some of the vessels.

Consequently, Method 1 can be applied to 32 vessels from the original database of 44, considering an upper boundary level of 3000 tons of DWT. In contrast, Method 2 only applicable for draught $T = 1.5 \cdot D$ (where D is the propeller diameter), which is very restrictive. Therefore, an original database consisting of 44 vessels was reduced to only one vessel, when Method 2 was considered. Hence, the vast difference between the methods' limitations was obvious from the start. Generally speaking, the draught required for Method 2 is not a design draught and, thus, a corresponding *DWT* will not be directly available for the analysis, in order to evaluate *EEDI* (attained and required). Therefore, this method commonly requires additional documentation, such as *Trim and Stability Booklet* for each specific vessel, where necessary input parameters for *EEDI* assessment can be found. Method 2 provides a limit of 6000 tons of *DWT* and covers all vessels in the database, when just a *DWT* is considered.

However, in order to achieve a comparison under an applicability limit for both methods, the assessment is performed for the vessels having an equal draught of 1.5D, taking into account the aforementioned, more restricted draught constraint of Method 2. This does not mean that the design draught of vessels is 1.5D, since it is quite the opposite for almost all the vessels except one, as previously mentioned. Despite the implication that the draught of all the vessels is, indeed, defined as 1.5D, for the purpose of the analysis and the corresponding volumetric displacement it is obtained according to the linear interpolation between parameters available for other draughts. Volumetric displacement is necessary for *DWT* evaluation and presents an input for *EEDI* calculations. Finally, after applied limitations and interpolation corrections, four cargo vessels remained for assessment, see Table 3.

Tab. 3. Vessels' main particulars

No.	L_{wl} [m]	B_{wl} [m]	T[m]	∇ [m^3]	*DWT* [m]
1	109.3	14.00	2.78	3530.9	2771.8
2	110.0	11.40	2.40	2578.4	2024.0
3	82.9	9.50	2.32	1607.1	1261.6
4	93.3	11.5	2.40	2206.0	1607.0

The analysis of energy efficiency was performed according to the following constraints:

- Waterway depth - h = 5 m (for shallow water) and waterway breadth - b = 400 m;
- Waterway depth - h = 8 m (for deep water) and waterway breadth - b = 400 m.

RESULTS

In the following, the calculation of energy efficiency indices and the comparison of both methods are presented, based on the procedures described in previous sections.

METHOD 1

Attained energy efficiency index is dependent on brake power, not on delivered power. Hence, a shaft efficiency coefficient of 0.98 was applied to estimate the brake power of the vessels. Attained and required *EEDI** are not expressed as one value (as is the case for sea-going ships, where *EEDI* is calculated for 75% of main engine power). Here, both values of (attained and required) *EEDI** are estimated for a range of speeds. Therefore, various speeds (10, 12, 14, 16, 18 and 20 km/h) were applied, considering the method's limits of applicability. The comparison between attained and required energy efficiency index for shallow water was assessed according to Method 1, as shown in Table 4 and Fig. 1. Grey cells represent the cases in which the energy efficiency criteria are not satisfied – see 12 km/h and 14 km/h for vessels no. 1. At 18 and 20 km/h, corresponding Froude numbers exceed the applicability criteria, and so the consequent results are not shown. Moreover, results for the deep water condition are shown in Table 5 and Fig. 2, with grey cells representing the failed criteria.

The results show that all four vessels satisfy the requirements for a lower speed range when a deep water condition is considered. For higher speeds, attained *EEDI** values are significantly above the required limit, making their navigation less efficient. Therefore, it seems that, according to the results, vessels navigating deep-water conditions would be less effective than in shallow-water conditions, which is quite unsound.

Tab. 4. Energy efficiency for shallow water (Method 1)

No.	Attained *EEDI**				Required *EEDI**			
	10 km/h	12 km/h	14 km/h	16 km/h	10 km/h	12 km/h	14 km/h	16 km/h
1	3.74	4.98	7.39	11.45	3.80	4.65	7.14	11.93
2	3.27	4.50	6.39	9.58	4.14	5.05	7.74	12.78
3	3.66	4.88	7.41	11.76	4.71	5.72	8.73	14.16
4	3.93	5.25	7.84	12.18	4.41	5.37	8.21	13.43

Tab. 5. Energy efficiency for deep water (Method 1)

No.	Attained *EEDI**					
	10 km/h	12 km/h	14 km/h	16 km/h	18 km/h	20 km/h
1	3.74	4.98	6.63	8.88	11.98	16.35
2	3.27	4.50	6.06	8.06	10.69	14.30
3	3.66	4.88	6.53	8.75	11.78	16.02
4	3.93	5.25	7.02	9.41	12.67	17.24

No.	Required *EEDI**					
	10 km/h	12 km/h	14 km/h	16 km/h	18 km/h	20 km/h
1	3.80	4.65	7.74	7.05	8.67	11.31
2	4.14	5.05	6.24	7.64	9.36	12.13
3	4.71	5.72	7.06	8.62	10.51	13.47
4	4.41	5.37	6.63	8.10	9.91	12.77

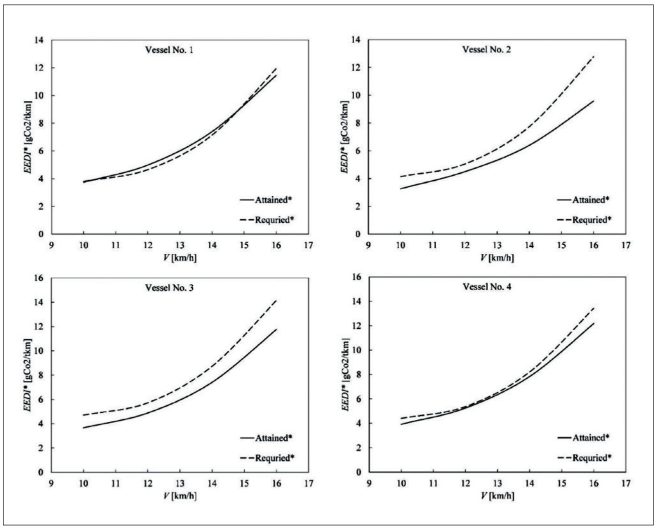

Fig. 1. Energy efficiency for shallow water (Method 1)

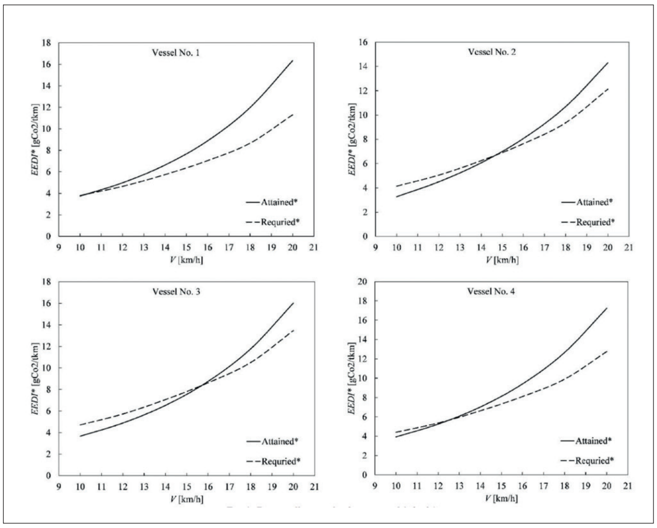

Fig. 2. Energy efficiency for deep water (Method 1)

METHOD 2

Energy efficiency indices assessed according to Method 2 are given in Table 6, for shallow and deep water, with grey cells representing the failed criteria. Note that river trial results (speed – power curves) have to be available prior to the *EEDI* estimation in order to evaluate the vessel's speed. Since the river trials results are not offered in the database, the delivered power was obtained using the mathematical model described and offered in [15]. Required EEDI is a function of the speed of the water, so the calculation was performed for 2, 4 and 6 km/h. However, the method is not able to consider the dependency between *EEDI* and the vessel speed, so the corresponding diagrams, as in the case of Method 1, could not be produced. Thus, this method allows calculation of energy indices for just one value of speed.

Method 2 appears to be less conservative than Method 1, when results for shallow water are considered, since attained *EEDI* values are approximately 40% less than required ones, on average. In the case of deep water, required *EEDI* values for all three water speeds are unchanged for each vessel, because they are only a function of *DWT* and not the speed of the river. Therefore, as the speed of the water is increased, an attained

Tab. 6. Energy efficiency for shallow and deep water (Method 2)

	Shallow water			Deep water		
No.	Speed of water – 2 km/h					
	V_s	Attained *EEDI*	Required *EEDI*	V_s	Attained *EEDI*	Required *EEDI*
1	14.23	14.93	23.89	14.97	12.34	14.36
2	14.79	14.56	24.47	15.50	11.92	15.28
3	14.21	15.35	25.99	15.11	12.23	16.93
4	14.08	15.35	25.12	14.73	12.55	16.02

	Shallow water			Deep water		
No.	Speed of water – 4 km/h					
	V_s	Attained *EEDI*	Required *EEDI*	V_s	Attained *EEDI*	Required *EEDI*
1	12.23	17.37	28.80	12.97	14.25	14.36
2	12.79	16.84	29.60	13.50	13.69	15.28
3	12.21	17.87	31.71	13.11	14.10	16.93
4	12.08	17.87	30.51	12.73	14.52	16.02

	Shallow water			Deep water		
No.	Speed of water – 6 km/h					
	V_s	Attained *EEDI*	Required *EEDI*	V_s	Attained *EEDI*	Required *EEDI*
1	10.23	20.77	36.29	10.97	16.85	14.36
2	10.79	19.96	37.86	11.50	16.07	15.28
3	10.21	21.37	41.97	11.11	16.63	16.93
4	10.08	21.41	39.63	10.73	17.22	16.02

EEDI is closer to the required limit. Hence, an attained *EEDI* is larger than that required for the 6 km/h speed of the river, for vessels no. 1, 2 and 4.

COMPARISON BETWEEN METHOD 1 AND METHOD 2

Method 1 gives a range of attained and required energy efficiency indices for various speeds of the vessel. However, Method 2 would provide the specific (one) attained and required energy efficiency value at delivered power for a specific speed. In order to compare the two methods, the specific attained and required *EEDI* values were obtained by applying the required speed (one value) derived from Method 2 into Method 1. This procedure was performed for three water speeds, while including shallow and deep-water conditions, see Table 7 (grey cells represent failed criteria). The difference between the two methods is illustrated in Fig. 3.

Since Method 1 is scaled to Method 2, both methods can be compared (Fig. 3): Method 1 (Table 7) vs. Method 2 (Table 6). Vessel No. 1 does not comply with the required *EEDI* in both shallow and deep-water conditions, in specific cases in Method 1. Despite this, the same vessel satisfies Method 2 in all cases, except deep water conditions where the water speed is 6 km/h. Furthermore, vessel No. 3 met the requirements in all cases and methods. Vessels No. 2 and No. 4 did not satisfy the Method 2 requirements for deep water conditions at a river speed of 6 km/h, but did comply with the requirements for the same river speed if Method 1 was considered. Nonetheless, for the same method, both vessels did not meet the required *EEDI* for 2 km/h of river speed, while vessel No. 4 did not even comply with the criterion when considering 4 km/h of river speed.

In general, as seen from the diagrams in Fig. 3, Method 2 provides two to five times larger values of energy efficiency indices (attained and required) than Method 1, for the river speeds of 2, 4 and 6 km/h and the same navigation conditions. Nonetheless, it should be noted that a different specific fuel consumption (SFC) was used in each method: 200 g/kWh for Method 1 and 220 g/kWh for Method 2. And yet, 10% of SFC difference could not lead to such a significant difference in energy efficiency indices.

Tab. 7. Energy efficiency for shallow and deep water (specific Method 1)

No.	Shallow water			Deep water		
	Speed of water – 2 km/h					
	V_s	Attained *EEDI**	Required *EEDI**	V_s	Attained *EEDI**	Required *EEDI**
1	14.23	7.73	7.53	14.97	7.64	6.35
2	14.79	7.28	9.30	15.50	7.51	7.27
3	14.21	7.70	9.15	15.11	7.68	7.91
4	14.08	7.96	8.36	14.73	7.81	7.14

No.	Shallow water			Deep water		
	Speed of water – 4 km/h					
	V_s	Attained *EEDI**	Required *EEDI**	V_s	Attained *EEDI**	Required *EEDI**
1	12.23	5.20	4.85	12.97	5.72	5.15
2	12.79	5.20	5.90	13.50	5.63	5.92
3	12.21	5.11	5.95	13.11	5.73	6.43
4	12.08	5.34	5.45	12.73	5.84	5.80

No.	Shallow water			Deep water		
	Speed of water – 6 km/h					
	V_s	Attained *EEDI**	Required *EEDI**	V_s	Attained *EEDI**	Required *EEDI**
1	10.23	3.82	3.81	10.97	4.30	4.18
2	10.79	3.64	4.28	11.50	4.16	4.79
3	10.21	3.69	4.71	11.11	4.30	5.22
4	10.08	3.95	4.41	10.73	4.37	4.72

CONCLUSION

Method 1 gives attained and required energy efficiency indices for a range of speeds and within less sensitive constraints than in Method 2. Therefore, such rigid limitations pose a great disadvantage in Method 2. This drawback is expressed through the draught requirement, which should be defined as 1.5*D* in order to use the method. Therefore, new

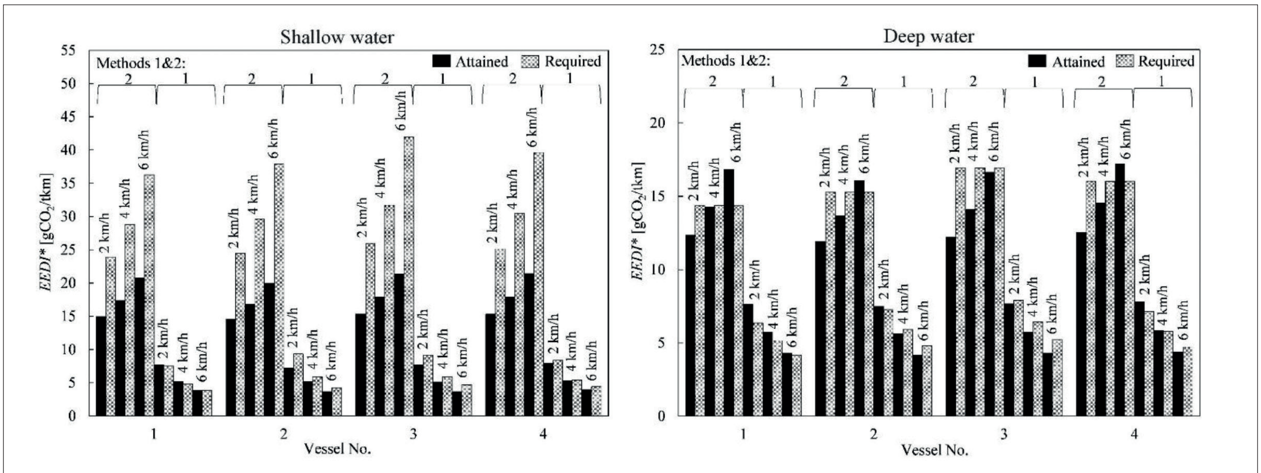

Fig. 3. Comparison between methods in shallow water conditions (left) and deep water conditions (right): 1 – specific Method 1 and 2 – Method 2

speed-power tests (river trials) should be conducted at this specific draught for the application of the method. Nonetheless, a potentially available speed-power curve would not be useful here. Although Method 1 is not so restrictive, it does not take into account the speed of the water. Moreover, there is a 10% difference in specific fuel consumption input between the methods, but this could not lead to a significant difference in the results. Furthermore, the results differ when both methods become comparable. It is interesting that, according to Method 2, shallow water required *EEDI* is quite large. In general, in a considerable number of cases, the vessels appear to be more energy efficient in shallow water than in deep water. This is quite improbable in practice, so the next step would be to address such a drawback within the methods.

Regarding the persistent issue arising from the power-speed curve estimation as an input, a real-time engine power measurement could be introduced during the navigation instead; followed by installation of an engine power limiter. Both could manage and optimise the real-time engine power to achieve energy efficiency under the limitations during the navigation. Therefore, in order to address the reliable navigation condition, attained energy efficiency should be measured rather than calculated.

It seems that the proposed regulations would not be able to induce the development of technology with respect to energy efficiency in years to come. The vessel designs considered here are the same as they were decades ago. This means that, according to the results, most of them do not need any improvements in terms of energy efficiency.

Nonetheless, the obvious conclusion is that inland waterway vessels' energy efficiency methods need to be harmonised when addressing the issues reported in this paper. Inland waterway authorities should provide more 'easy to use' solutions, such as in the maritime industry.

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