www.cesni.eu

EVALUATING THE ENERGY REQUIREMENT OF INLAND VESSELS USING ENERGY EFFICIENCY INDICES

June 2020

CESNI work programme 2019-2021, task PT-26

Disclaimer

The facts presented in this study and opinions expressed are those of the authors and do not necessarily also represent the position of the BMVI or to the CESNI on the subject in question. Use of the knowledge, information or data contained in this document is at the user's own risk. The BMVI or CESNI shall in no way be liable for use of the knowledge, information or data contained in this document or any ensuing consequence.

R&D project 40.0399/2017 Evaluating the energy requirement of inland vessels using energy efficiency indices

Executive summary of final report no. 2252

This is an English translation of the report prepared within the context of CESNI/PT.

This translation is not a publication by DST or the Federal Ministry of Transport and Digital Infrastructure.

The basis of the translation is the German report

April 2019

Client:
Federal German Ministry of Transport
and Digital Infrastructure
Robert-Schuman-Platz 1
53175 Bonn

Entwicklungszentrum für Schiffstechnik und Transportsysteme e.V.

Entwicklungszentrum für Schiffstechnik und Transportsysteme e.V.
DST – Development Centre for Ship Technology and Transport Systems

Oststraße 77
47057 Duisburg

Tel. +49 203 99369-0
Fax +49 203 99369-70
e-mail dst@dst-org.de
web www.dst-org.de

Member of the German Federation of Industrial Cooperative Research Associations ""Otto von Guericke" e. V."

Member of the Johannes-Rau-Forschungsgemeinschaft e. V.

Institute at the University of Duisburg-Essen

Member of the International Towing Tank Conference

Member of the Center of Maritime Technologies e. V.

Table of Contents

List of figures

List of abbreviations

B	[m]	Vessel breadth
CF[1]	[-]	Conversion factor to CO_2
dw	[t]	Deadweight
D	[nm], [km]	Distance
$EEDI$	$\left[\frac{g_{CO2}}{t\ km}\right]$	Energy Efficiency Design Index
$EEOI$	$\left[\frac{g_{CO2}}{t\ km}\right]$	Energy Efficiency Operational Indicator
Fr_h	[-]	Depth Froude number
h	[m]	Water depth
j	[-]	Transport number
L	[m]	Vessel length
SFC[2]	$\left[\frac{g}{kWh}\right]$	specific fuel consumption 215 g/kWh
T	[m]	Draught
P_D (vessel type) Berg (upstream) or Tal (downstream) or Mittel (mean value)	[kW]	Shaft power index: Vessel type (MS=MV, TMS = tanker, SV = pushed convoy, FGS = passenger vessel), index: upstream or downstream (shaft power upstream or downstream) or mean (time-weighted mean shaft power)
P_{ME}[3]	[kW]	75% of total installed shaft power
V_{ref}	[kn]	Speed
V_{str}	$\left[\frac{km}{h}\right]$	Current speed
$V_{üG}$	$\left[\frac{km}{h}\right], \left[\frac{m}{s}\right]$	Speed over the ground
$V_{üG\ Berg}$	$\left[\frac{km}{h}\right]$	Speed over the ground upstream
$V_{üG\ Tal}$	$\left[\frac{km}{h}\right]$	Speed over the ground downstream
Δ	[t]	Displacement $[m^3] \cdot density_{water}\ [t/m^3]$

1 MEPC 245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships", ISO 8217.

2 MEPC 215(63) "2012 Guidelines for calculation of Reference Lines for use with the Energy Efficiency Design Index EEDI", a specific fuel consumption of 220 g /kWh was calculated for inland waterway vessels.

3 MEPC 215(63) "2012 Guidelines for calculation of Reference Lines for use with the Energy Efficiency Design Index EEDI".

Summary

This draft investigated the possibility of evaluating the energy efficiency of inland waterway vessels using energy efficiency indices. A rating system for the energy efficiency of inland waterway vessels seems sensible supporting shipowners as it does with their investment decisions and ensuring the transparency of economic incentive systems. It also enables the development of a sound frame of reference for public subsidy systems that is independent of the measures taken.

This study was based on the maritime Energy Efficiency Design Index (EEDI). The differing parameters specific to inland navigation were developed following a brief description of the approach to evaluating the energy efficiency of seagoing vessels. Of particular note here is the fact that inland waterway vessels use significantly lower engine power than the maximum available installed power, which is only needed for occasional extreme operating situations where high power is required. On the Rhine, for example, a laden motor freighter with a length of 110 m, a breadth of 11.45 m and a draught of 2.8 m at average to high water levels heading upstream will use powers of between approximately 600 kW and 1000 kW and downstream of approximately 100 kW to 300 kW. But the installed propulsion power can be 2500 kW or more. An operating point with a propulsion power of 75% of the total installed propulsion power, as in the case of seagoing vessels, is therefore not a representative operating point for an inland navigation vessel.

Other important factors influencing the energy efficiency of inland navigation vessels are navigation area and water conditions because they largely dictate the minimum draught at which the operator is still prepared to operate the vessel. In turn, this minimum draught determines the propeller diameter and/or propulsion concept. Propeller diameter plays an important role in the energy-efficient operation of the vessel at all draughts. Vessels that have been designed for small draughts would be significantly disadvantaged when a large reference draught is considered, such as the maximum draught to be found in the inland navigation vessel certificate. We should also mention the significant differences between vessel types as concerns own weight and thus deadweight, as well as the very different pushed convoy configurations. The use of deadweight in determining transport performance as a component of the *EEDI* is therefore not appropriate for all vessel types.

A possible approach for inland navigation vessels was developed having regard to these and other parameters, based on the derivation of the *EEDI* for seagoing vessels. This entailed power (75% of the installed power) being replaced by use of a shaft power dependent on type of vessel and the reference speed V_{ref} being replaced by speed over the ground $V_{\mathrm{üG}}$. Deadweight is used except for vessel class 4, passenger vessels. The displacement mass Δ is used for passenger vessels to minimise the number of passenger vessel types (day excursion vessel, cabin vessel or passenger vessel sizes that depend on passenger numbers).

A specific fuel consumption of 220 g /kWh should be used for inland navigation vessels instead of 215 g/kWh for seagoing vessels. This figure is derived from the test-bed reports for inland vessel engines.

EEDI values for the vessel variants were calculated using this approach and displayed in the form of scatter diagrams. The required input data (power, speed and deadweights) was derived from power forecasts previously calculated at the DST based on model test results for different types of vessel, water depths and speeds etc. A total of 500 operating profiles from DST model tests were examined and analysed. It was assumed that this data is a representative reflection of the hydrodynamically determined energy requirement to achieve a target speed.

The power consumption of additional energy generators for

- the nautical and technical operation of the vessel both underway and stationary
- the cargo
- the emergency power supply
- the bow thruster system
- the ballast system
- crew quarters and facilities

could not be taken into consideration as this data is not available. In determining the $EEDI_{\mathrm{Binnen}}$ for inland vessels, it was proposed to consider forward propulsion shaft power only. This could also eliminate the relatively high investment costs for equipping all main and auxiliary generator sets with power consumption measuring equipment.

The next step attempted to minimise the variances in the energy efficiency indices for different conditions (water depth, draught etc.) and vessel types or formations using specific regression analyses, thus increasing the *EEDIs*' scope of application. Three evaluation approaches were subjected to quantitative analysis, an evaluation based respectively on the depth Froude number, speed over the ground and a parameterised shaft power. It was possible to describe shaft power by means of a function dependent on water depth, deadweight or displacement mass and the vessel's breadth. This was the preferred approach in principle.

Upper limits or envelopes were calculated for the data determined for each vessel type using the preferred evaluation approach, which consequently depend on the vessels' primary parameters (draught, displacement mass or deadweight, vessel breadth, vessel length and shaft powers) and on the waterway conditions (water depth, channel width and current).

A comparison between the findings from the model testing and full-scale measurements resulted in some adjustments, i.e. shifts or changes in the trajectory of the envelope graph lines. A total of 65 operating profiles from full-scale DST measurements were analysed.

The envelope graph curves (lines) are the trend lines of an $EEDI_{\text{Binnen}}$. All calculated $EEDI_{\text{Binnen}}$ values from the model and full-scale investigations of the vessels included in the study fall below these trend lines.

This yields the hypothesis, if the vessels considered in the regression analysis are representative of the existing fleet, that the actual $EEDI_{\text{Binnen}}$ values for the vessels in the existing fleet will not exceed the calculated $EEDI_{\text{Binnen}}$ trend lines.

4 classes of vessel were ultimately required to properly represent the inland vessel fleet:

- Vessel class 1: dry cargo and container vessels
- Vessel class 2: tankers
- Vessel class 3: pushed convoys
- Vessel class 4: passenger vessels

For vessel classes 1-3 the shaft power to be used depends on deadweight dw, and for class 4 on the displacement mass Δ. For all vessel classes, the shaft power also depends on water depth and vessel breadth. The validity ranges of the calculated relationships, e.g. relative to water depth h, vessel draught T, current V_{str}, vessel breadth B and the h/T relationship was stated in all cases.

The regression analyses then culminated in two proposed approaches for evaluating inland vessel energy efficiency. The first simplified proposal applies to all vessels. The test voyage to determine what *EEDI* has been attained can be undertaken in deep water provided that such depths are available. This treatment can be classified as being equivalent to the *EEDI* for seagoing vessels. In the case of the second proposal, a distinction is made between different navigation areas, zone 3 (Rhine) and zone 4, including canals. Consequently, provided that the consumption for forward propulsion is captured by means of the consumption indicator, or the shaft power is measured, the inland navigation vessels' $EEDI_{Binnen}$ can be performed in deep and, sideways, virtually unlimited water, as well as when underway on rivers with a current and channel widths consistent with those of the Rhine using the established parameters. Likewise, the $EEDI_{Binnen}$ can be determined when operating on a standard canal. Representative test areas should be used in all cases.

The practical approach to determining the energy efficiency during the test voyage was subjected to critical scrutiny. Admittedly, for new ships, an *EEDI* voyage might not incur high, or indeed any, additional investment costs because the engines typically are fitted with a consumption indicator. The accuracy of these indicators would need to be checked. Vessels in the existing fleet, however, need to be equipped with a gauge to determine the shaft power.

The objective of the present concept is to develop a representative Energy Efficiency Index ($EEDI_{Binnen}$) for inland vessels having regard to their navigaton area. As the $EEDI_{Binnen}$ only considers one vessel operating point, relative to the many possible operating points, one could well imagine other concepts and approaches to proposing an Energy Efficiency Index.

The proposal put forward here is intended to stimulate discussion on this topic within the navigation industry.

In addition to the concrete proposals for the $EEDI_{Binnen}$, an approach to how the Energy Efficiency Operating Indicator (*EEOI*) should be handled was also developed.

Compared with the $EEDI_{Binnen}$ the *EEOI* only represents one operating point. The *EEOI* takes account of total consumption, or CO_2 emissions relative to the transport volume and transportation distance. A significant perceived challenge was that capturing energy consumption on the same sections of water on different days results in different results of limited comparability owing to different water conditions, such as water levels and current speeds.

A proposal for determining an *EEOI* has been devised which enables an energy assessment of individual inland navigation vessels to be conducted for their respective vessel classes and in their navigation area, or on specific stretches of water. This concept entails subdividing the voyage segment as soon as there is any material change to the waterway parameters. As before, not only is the fuel consumption for forward propulsion factored in but also the vessel's entire consumption for a section of waterway or the entire section. The fuel consumption can be read off from the fuel tanks' filling level indicators and documented.

The sections of waterway should however be sufficiently long to permit the filling level indicators to give an accurate reading of fuel consumption. Depending on the tanks' size and geometry and the accuracy with which the filling level indicators can be read, an appropriate quantity of fuel should be consumed. For example, to determine an operating point for a period of approximately 1 to 2 hours (the time required for an *EEDI* journey) the indicated differences in filling level are too small to establish the exact fuel consumption.

The method in the proposal for determining the *EEOI* can be performed by the ship operators themselves. To this end, representative sections within the waterway network should be used suitable for determining an *EEOI*.

For new ships, an $EEDI_{Binnen}$ can be performed in deep water or on a representative section using calibrated fuel consumption indicators.

The *EEOI* should be continually calculated for the waterway sections being operated on and the total transport route, both for the existing fleet and for new ships.

A gradation of 15% and of 25% relative to the established relations was proposed for new ships to reduce inland navigation vessels' CO_2 emissions. State-of-the-art technical measures could be used to achieve this reduction. Vessels in the existing fleet can emit between 15 % and 25 % less CO_2 relative to the $EEDIs_{\text{Trendlinie (trendline)}}$ (base). However, to achieve an absolute reduction in CO_2 emissions of 15% - 25% requires extensive conversion measures, such as changing the shape of the vessel's stern and/or fore-section, optimising the propulsion and steering system and/or increasing the vessel's length.

The Energy Efficiency Indices for inland vessels that have been developed help capture the CO_2 emissions from freight transport on inland waterways. The socio-political requirement for a significant reduction in CO_2 emissions compared with 1990 presupposes that current inland navigation vessel emissions can be quantified, and any changes measured. It has not been possible to quantify earlier developments in inland navigation vessel construction and improvements in operating processes resulting in lower emissions from water-borne transport. Using Energy Efficiency Indices within a given framework it is possible to capture the current status and evaluate optimisations. Given the critical importance of Energy Efficiency Indices in evaluating CO_2 emissions, the baseline conditions for the indices in this report tend to be excessively skewed towards model tests relative to full-scale conditions such that a more pronounced demarcation may be required. We therefore recommend that the project be continued with the emphasis on “large-scale measurements for checking and validating the baseline conditions for the Energy Efficiency Index in real life operation”.

1 Introduction

1.1 Background and motivation

The Federal German Ministry of Transport and Digital Infrastructure (BMVI) has commissioned the *Entwicklungszentrum für Schiffstechnik und Transportsysteme e.V.* (Development centre for ship technology and transport systems) to develop and draw up a concept for evaluating energy consumption by inland vessels. The preferred approach is based on the maritime shipping approach using so-called Energy Efficiency Indices (*EEDI*, *EEOI* inter alia).

The Energy-Efficiency Design-Index for maritime navigation is defined as per the equation (1) and is expressed in $\frac{\mathrm{g\,CO_2}}{t\,kn}$.

$$EEDI = \frac{CF \cdot SFC \cdot P_{\mathrm{ME}}}{V_{\mathrm{ref}} \cdot dw} \qquad (1)$$

$EEDI$	$[\frac{\mathrm{g\,CO_2}}{\mathrm{t\,kn}}]$	Energy Efficiency Design Index
CF	$[\frac{\mathrm{g\,CO_2}}{\mathrm{g\,Diesel}}]$	CO_2 diesel equivalent (3,206 $\frac{\mathrm{g\,CO_2}}{\mathrm{g\,Diesel}}$)
SFC	$[\frac{\mathrm{gDiesel}}{\mathrm{kWh}}]$	specific fuel consumption (215 g/kWh)
P_{ME}	[kW]	75% of total installed propulsion power
V_{ref}	[kn]	Reference speed in deep water and with no swell
dw	[t]	Deadweight

The CO_2 equivalent *CF* of 3.206 $\mathrm{g_{CO2}/g_{\ Diesel}}$ corresponds to the guideline as per MEPC 245(66) "2014 Guidelines on the Calculation of the Attained EEDI for New Ships", ISO 8217".

MEPC 215(63) "2012 Guidelines for Calculation of Reference Lines for Use with the Energy Efficiency Design Index EEDI", indicates a specific fuel consumption *SFC* of 215 g/kWh.

The Energy-Efficiency Design-Indicator for maritime navigation is defined as per the equation (2) and is expressed in $\frac{\mathrm{g\,CO_2}}{t\,kn}$.

$$EEOI = \frac{FC_j \cdot CF_j}{m_{\mathrm{cargo}} \cdot D} \qquad (2)$$

$EEOI$	$[\frac{\mathrm{g\,CO_2}}{\mathrm{t\,nm}}]$	Energy Efficiency Operational Indicator
FC	[g*Diesel*]	Mass of fuel consumed
CF	$[\frac{\mathrm{g\,CO_2}}{\mathrm{g\,Diesel}}]$	CO_2 diesel equivalent (3,206 $\frac{\mathrm{g\,CO_2}}{\mathrm{g\,Diesel}}$)
m	[t]	Amount of cargo
D	[nm]	Distance
j	-	Transport number

Newly constructed vessels have had to comply with Energy Efficiency Design Index (*EEDI*) limits as of 1 January 2013 and are awarded an international energy efficiency (*IEE*) certificate. The *EEDI* stipulates the quantity of CO_2 greenhouse gas emissions relative to the transport performance with the intention of driving the development of innovative technical components in ship design, resulting in lower fuel consumption and consequently in CO_2 emissions.

The Energy Efficiency Operational Indicator (*EEOI*) has established itself alongside the *EEDI* and enables the ship operator to evaluate the energy efficiency of his vessel in operation based on actual fuel consumption. All technical measures implemented on the vessel and improvements, in route planning for example, or as a result of nautical assistance systems, are directly reflected in the *EEOI*. The *EEOI* is calculated in a similar way to the *EEDI*, but the *EEOI* captures actual CO_2 emissions during the vessel's operation relative to the product of quantity of cargo carried and transportation distance.

The development of both indices began around the beginning of the 1990s and is currently updated to reflect the state-of-the-art. But not all vessel types are yet included. Vessels that are subject to trade-related restrictions or local circumstances are not yet covered. Nor are seagoing vessels.

A similar energy efficiency rating system for inland vessels is deemed opportune and affords the following benefits:

1. The shipowner is supported in his investment decisions because there is an evaluation of his vessel in terms of energy efficiency or CO_2 emissions. Likewise, a good rating increases the resale value of his vessel.
2. Shipyards find it easier to sell energy or climate-efficient new vessels as the benefit of the increased investment cost is corroborated by the favourable rating.
3. Economic incentive systems are underpinned by an easy-to-use and transparent mechanism. For example, vessels with a good classification are eligible for larger discounts on port or waterway taxes than vessels with a poor, or lower, rating.
4. Government subsidy systems (including in this case the BMWI support programme) that take account of energy efficiency enjoy a broader and, above all, unconditional reference basis. The subsidy can be geared to achieving a specific target (for example the best energy consumption class). It is then up to the vessel owner to select the most appropriate measure for achieving the target.
5. The energy consumption classification could also be incorporated directly as an important component into an inland vessel environmental certification system (Green Label, Blue Angel).

1.2 Objective and conditions

The basic principles and proposals for inland vessel energy efficiency indices need to be drawn up against the aforementioned background. This needs to consider the environment within which inland vessels operate on different inland waterways and highlight the appropriate criteria for assessing energy efficiency. The chosen approach should not be restricted to new ships but should also include the existing inland vessel fleet.

The overarching objective is to develop a comprehensive energy efficiency index for inland vessels. This should provide for gradations or sub-variants, e.g. for different types and sizes of vessel. A rough estimate needs to be developed covering all vessels together with a detailed assessment, for example for individual vessel configurations such as single ships or pushed convoys.

1.3 General concept

The general concept for assessing inland vessel energy efficiency mirrors the maritime navigation approach. A variant of the *EEDI* tailored to inland navigation was applied. It was used to analyse performance forecasts from model tests. Appropriate *EEDI* trend lines were derived from the regression analysis results and proposed.

2 Calculation approach and method

The first step was to develop a mathematical formula for $EEDI_{\text{Inland}}$, see equations (3) and (4). Depending on vessel type, deadweight dw is replaced by displacement mass Δ.

$$EEDI_{\text{Binnen}} = \frac{CF \cdot SFC \cdot P_{\text{D (vessel type) (upstream or downstream or mean value)}}}{V_{\text{ü}G} \cdot dw} \quad (3)$$

or

$$EEDI_{\text{Binnen}} = \frac{CF \cdot SFC \cdot P_{\text{D (vessel type) (upstream or downstream or mean value)}}}{V_{\text{ü}G} \cdot \Delta} \quad (4)$$

CF	$[\frac{\text{g CO}_2}{\text{g Diesel}}]$	CO_2 diesel equivalent (3,206 $\frac{\text{g CO}_2}{\text{g Diesel}}$)
SFC	$[\frac{\text{gDiesel}}{\text{kWh}}]$	specific fuel consumption (220g/kWh)
$P_{\text{D (vessel type) (upstream or downstream or mean value)}}$	[kW]	Shaft power used, depends on vessel type and/or journey of travel upstream or downstream or an average shaft power
$V_{\text{ü}G}$	[km/h]	Speed over the ground
dw	[t]	Deadweight
Δ	[t]	Displacement mass

The CO_2 equivalent CF of 3.206 g_{CO2}/g_{Diesel} was used as per MEPC 245(66) "2014 Guidelines on the Calculation of the Attained EEDI for New Ships", ISO 8217".

According to MEPC 215(63) "2012 Guidelines for Calculation of Reference Lines for Use with the Energy-Efficiency Design-Index EEDI" the specific fuel consumption SFC is 215 g/kWh. This fuel consumption is based on 75% of nominal power. The specific fuel consumption is higher at a lower part load than 75% of nominal power. An analysis of inland vessel engine test-bed reports revealed that an average specific fuel consumption of 220 g/kWh is required within a performance range of 25% to 100% of nominal power. This consumption was therefore used consistently.

A percentage proportion of the engine's nominal power is not used because the same vessels can have engines of different power for various reasons.

The shaft power to be used $P_{\text{D (vessel type) (Berg oder Tal oder Mittel = upstream or downstream or mean value)}}$ was determined based on model test results and depends on vessel type and on water conditions (upstream or downstream or deep water and no current).

EEDI values for the vessel variants were calculated using equations (3) and/or (4) and displayed in the form of scatter diagrams. The data so generated gave rise to upper limits or envelopes, which therefore depend on the principal vessel parameters (draught, displacement mass or deadweight, vessel breadth, vessel length and shaft powers) and on waterway conditions (water depth, channel width and current).

It was also attempted to minimise the variances in the energy efficiency indices for different conditions (water depth, draught etc.) and vessel types or formations using appropriate regression analyses, thus increasing the *EEDIs*' scope of application and reducing the number of subcategories required.

The depth Froude number Fr_{h} and speed over the ground $V_{\mathrm{üG}}$ were appropriate for vessels operating on a restricted waterway. But a deliberate reduction in the shaft power employed also successfully reduced the data variances. For example, shaft power can be described by means of a function dependent on water depth, deadweight or displacement mass and the vessel's breadth.

In summary, three evaluation approaches were investigated:

1. **Analysis using the Depth Froude number Fr_{h}**

   The vessels' model test data are analysed based on a depth Froude number dependent on water depth

$$Fr_{\mathrm{h}} = \frac{V_{\mathrm{üG}}}{\sqrt{g \cdot h}} \qquad (5)$$

Fr_{h}	[-]	depth Froude number
$V_{\mathrm{üG}}$	[m/s]	Vessel speed, speed over the ground
g	[m/s²]	Acceleration due to gravity
h	[m]	Water depth

   and an $EEDI_{\mathrm{Binnen}}$ calculated taking account of deadweight and displacement mass.

2. **Regression of speed over the ground using water depth, displacement and/or deadweight**

   The evaluation based on speed over the ground had the same objective of achieving a small spread in *EEDI* data. It involved describing the speed over the ground by means of a functional relationship using water depth and to some extent the vessel's breadth as a variable parameter in addition to deadweight or displacement mass. The shaft power was inferred from the model test data in accordance with the calculation of speed over the ground.

3. **Regression of shaft power using water depth, deadweight and vessel breadth**

   The evaluation based on deadweight-dependent shaft power envisages shaft power being described in terms of a functional relationship. This entailed water depth and to some extent the vessel's breadth being used as a variable parameter in addition to deadweight or displacement mass.

The speed over the ground was inferred from the model test data in accordance with the calculation of shaft power.

There was also an attempt to ensure that the equipment required to establish the existing *EEDI* is appropriate and that the vessel or waterway is subject to the lease possible restrictions in terms of choice of draught or water depth.

The $EEDI_{\text{Inland}}$ trend lines generated for individual vessel groups were verified using results from large-scale measurements.

The first output from this analytical activity was a proposal for a general *EEDI*. An *EEDI* dependent on navigation area was then proposed.

3 Comments on the methodological concept

No additional consumers (generators, cargo or ballast pumps and the like) or renewable energy sources were considered in the approach. This information is typically unknown when model tests are being carried out and were therefore not available to the DST. Theoretical conditions of use are employed or additional allowances for further performance losses along the power train.

The following equations for determining power or for the $EEDI_{Binnen}$ trend lines (envelope limits) identified and proposed in the study are anonymized using Greek symbols. These are constants designated with $\alpha_{1-14}, \beta_{1-13}, \gamma_{1-8}, \delta_{1-7,} \varepsilon_{1-7}, \zeta_{1-5}, \eta_{1-4}, and\ \theta_{1,2}$.

The equations' characteristics are however shown. This condensed version focuses on the approach or rather the proposed concept for evaluating the energy efficiency of inland vessels. The associated constraints are identified.

This methodological concept illustrates one way of evaluating the energy efficiency of inland vessels and requires extensive validation and potentially modification, by means of deliberately selected large-scale measurements. The volume of large-scale data used in this work is limited.

4 Proposal for a general $EEDI_{Binnen}$

4.1 Vessel classes and constraints

This proposal differentiates solely between two vessel groups

- Vessel group A:
  - Vessel class 1, dry cargo vessels and container ships, MV
  - Vessel class 2, tankers, (TMS)
  - Vessel class 3, pushed convoys, (SV)
- Vessel group B:
  - Vessel class 4, passenger vessels, (FGS)

The same *EEDI* trend line is used for assessing all vessel classes, see Fig. 1. But the power to be used and the constraints differ.

4.1.1 Vessel class 1 - 3

Proof that an *EEDI* has been complied with must be provided for a water depth $h > 7.5$ m, e.g. in maritime waters or on inland lakes, as the case may be, and comply with the following constraints:

a) $T = 1.5 \cdot$ propeller diameter in the range between $2.0 \text{ m} \leq T \leq 3.2$ m

b) Shaft power as per the vessel type as in equation (6), (7) or (8)

$$P_{\text{D MS mean}} = \alpha_1 \cdot dw \quad [\text{kW}] \qquad (6)$$

$$P_{\text{D TMS mean}} = \alpha_2 \cdot dw \quad [\text{kW}] \qquad (7)$$

$$P_{\text{D SV mean}} = \left(\alpha_3 + \beta_1 \cdot EXP\left(\frac{B}{-\gamma_1}\right)\right) \cdot dw \quad [\text{kW}] \qquad (8)$$

During the test voyage to determine the $EEDI_{Binnen}$ the speed over the ground is measured with the appropriate shaft power setting $P_{\text{D (Vessel type) (mean)}}$ and the $EEDI_{Binnen}$ calculated as per equation (3).

$$EEDI_{\text{Binnen}} = \frac{CF \cdot SFC \cdot P_{\text{D (vessel type) (upstream or downstream or mean value)}}}{V_{\text{üG}} \cdot dw} \qquad (3)$$

The $EEDI_{Binnen}$ calculated using equation (3) should be smaller than the index calculated using equation (9) and accordingly fall below the $EEDI_{\text{trendline}}$ in Fig. 1 .

$$EEDI_{\text{trendline}} = \alpha_4 + \beta_2 \cdot EXP\left(\frac{dw}{-\gamma_2}\right) + \vartheta_1 \, EXP\left(\frac{dw}{-\delta_1}\right) \qquad (9)$$

CF	$\left[\frac{\text{g CO}_2}{\text{g Diesel}}\right]$	CO_2 diesel equivalent (3,206 $\frac{\text{g CO}_2}{\text{g Diesel}}$)
SFC	$\left[\frac{g\ Diesel}{kWh}\right]$	specific fuel consumption (220 $\frac{\text{g } Diesel}{\text{gkWh}}$)
$P_{\text{D (vessel type) (mean)}}$	[kW]	average shaft power, depends on vessel type
$V_{\ddot{u}G}$	$\left[\frac{km}{h}\right]$	Speed over the ground
dw	[t]	Deadweight
$EEDI_{\text{Binnen}}$	$\left[\frac{\text{g CO}_2}{t\ km}\right]$	Energy Efficiency Design Index Inland

4.1.2 Vessel class 4

The following general conditions apply for passenger vessels during the test voyage to determine the $EEDI_{Binnen}$:

a) The draught is as per the design draught, with slight variances as the case may be between +/- 5 %, and should be within the limits 0.6 m < T < 2.1 m.

b) The shaft power to be employed is to be determined as per the equation (10)

$$P_{\text{D PV mean}} = (\alpha_5 + \beta_3 \cdot EXP\ (\tfrac{\Delta}{-\gamma_3})) \cdot \Delta \qquad \text{[kW]} \qquad (10)$$

The speed achieved $V_{\text{üG}}$ with the shaft power setting is measured and the $EEDI_{Binnen}$ calculated using equation (4).

$$EEDI_{\text{Binnen}} = \frac{CF \cdot SFC \cdot P_{\text{D (vessel type) (upstream or downstream or mean value)}}}{V_{\ddot{u}G} \cdot \Delta} \qquad (4)$$

The $EEDI_{Binnen}$ calculated using equation (4) should be smaller than the index calculated using equation (11) and accordingly fall below the $EEDI_{\text{trendline}}$ in Fig. 1 .

$$EEDI_{\text{trendline}} = \alpha_4 + \beta_2 \cdot EXP\left(\frac{\Delta}{-\gamma_2}\right) + \vartheta_1 \cdot EXP\left(\frac{\Delta}{-\delta_1}\right) \qquad (11)$$

CF	$\left[\frac{\text{g CO}_2}{\text{g Diesel}}\right]$	CO_2 diesel equivalent (3,206 $\frac{\text{g CO}_2}{\text{g Diesel}}$)
SFC	$\left[\frac{gDiesel}{kWh}\right]$	specific fuel consumption (220 $\frac{\text{g } Diesel}{\text{kWh}}$)
$P_{\text{D (passenger vessel) (mean)}}$	[kW]	Average shaft power
$V_{\text{üG}}$	$\left[\frac{km}{h}\right]$	Speed over ground
Δ	[t]	Displacement mass
$EEDI_{\text{Binnen}}$	$\left[\frac{\text{g CO}_2}{t\ km}\right]$	Energy Efficiency Design Index Inland

The assessment for passenger vessels uses displacement mass instead of deadweight to avoid any further groupings within vessel class 4. This applies both for the assessment of shaft power and for the *EEDI* trend line.

In principle, all vessels in possession of, or which wish to obtain, a Rhine vessel inspection certificate, could comply with the aforementioned conditions for an *EEDI*. The restriction here is that the survey needs to be conducted in deep water with almost no current. Slight current influences may be minimised by specific upstream and downstream journeys, if appropriate.

New ships, which typically undergo the vessel certificate surveys in the Netherlands (Haringvliet), could perform the *EEDI* trips there at the same time. The existing German fleet would, for example, have to divert to inland lakes or maritime waters (waterway zone 2), but with the draught potentially restricted owing to the requirements of the navigation area (freeboard) or else the vessel not having any vessel certificate for this navigation area.

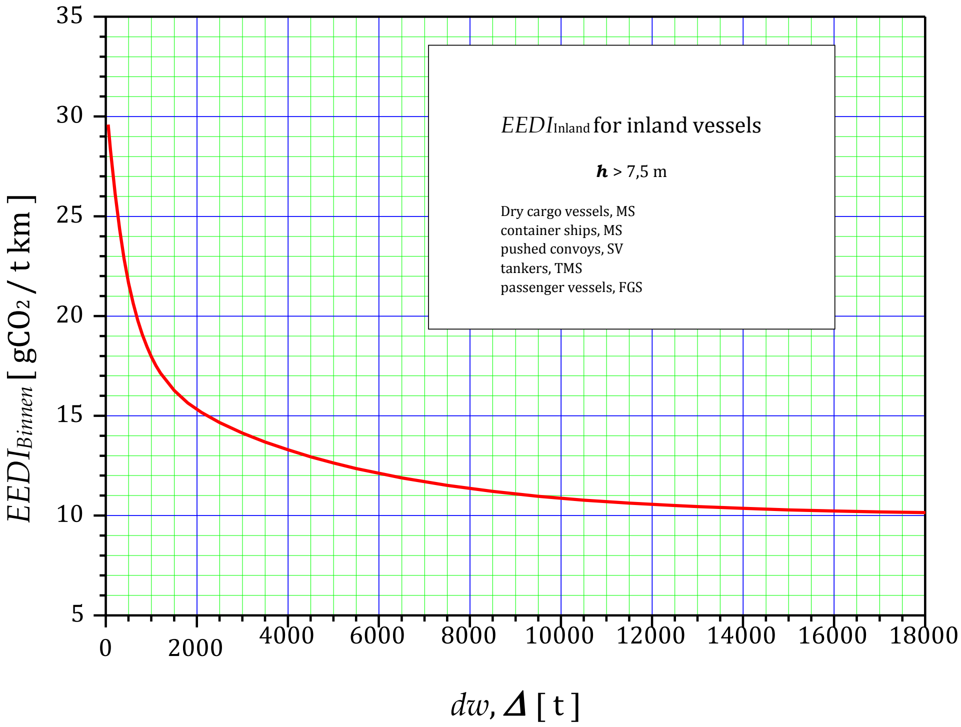

Fig. 1: $EEDI_{Binnen}$ trend line for inland vessels

For an additional general $EEDI_{Binnen}$ constraints could also be established for other appropriate waterway sectors using the same methodology. This would require appropriate test areas with defined water parameters (with no current) to be earmarked. Depending on these test areas' water parameters, the constraints will then be formulated.

5 Proposal for a navigation area-dependent *EEDI*Binnen

An $EEDI_{Binnen}$ dependent on navigation area is proposed having regard to water depth, current direction and current speed.

This entails differentiating two different navigation areas, described in accordance with the definition in the Inland Waterways Vessel Inspection Ordinance (BinSchUO).

- Zone 3, Rhine
- Zone 4

The various vessel types are divided into 4 classes depending on navigation area. They are to comply with the following constraints.

The test voyage is to be conducted in a upstream direction. The corresponding shaft power to be used is to be calculated.

5.1 Zone 3 waterways (Rhine)

5.1.1 Vessel class 1 (dry cargo vessels and container ships)

The following general conditions apply for dry cargo vessels and container ships during the test voyage to determine the $EEDI_{Binnen}$ in an upstream direction:

a) Draught: T = 1.5 · propeller diameter in the range 2.0 m ≤ T ≤ 2.8 m

b) Length: 40.0 m ≤ L ≤ 135.0 m

c) Width: 5.0 m < B < 17.0 m

d) Deadweight: 250 t ≤ dw ≤ 6000 t

e) Current speed: 2.0 km/h ≤ V_{str} ≤ 8.0 km/h

f) Water depth: 3.5 m ≤ h ≤ 7.5 m

g) Water depths/draught ratio: h/T ≥ 1.40

The shaft power to be employed is to be determined using equation (12)

$$P_{\mathrm{D\ Berg\ MS}} = \left(\alpha_6 + \beta_4 \cdot EXP(-\gamma_4 \cdot B) - \delta_2 \cdot EXP\left(\frac{\boldsymbol{h}}{-\varepsilon_1}\right)\right) \cdot dw \quad [\mathrm{kW}] \qquad (12)$$

During the test voyage the current speed must be known. The speed $V_{\mathrm{üG}}$ is measured with the shaft power setting $_{\mathrm{D\ Berg\ MS}}$ The $EEDI_{Binnen}$ is calculated as per equation (3).

$$EEDI_{\mathrm{Binnen}} = \frac{CF \cdot SFC \cdot P_{\mathrm{D\ (vessel\ type)\ (upstream\ or\ downstream\ or\ mean\ value)}}}{V_{\mathrm{ü}G} \cdot dw} \qquad (3)$$

The $EEDI_{Binnen}$ calculated using equation (3) should be smaller than the index calculated using equation (13) and accordingly fall below the current-dependent $EEDI_{Binnen\ trendline}$ in Fig. 2 .

$$EEDI_{MS\ Binnen\ trendline} =$$

$$(\alpha_7 + \beta_5 \cdot V_{str} + \gamma_5 \cdot V_{str}^2) + (\delta_3 + \varepsilon_2 \cdot V_{str} - \zeta_1 \cdot V_{str}^2 + \eta_1 \cdot V_{str}^3) \cdot EXP\left(\frac{dw}{-\theta_1}\right) \qquad (13)$$

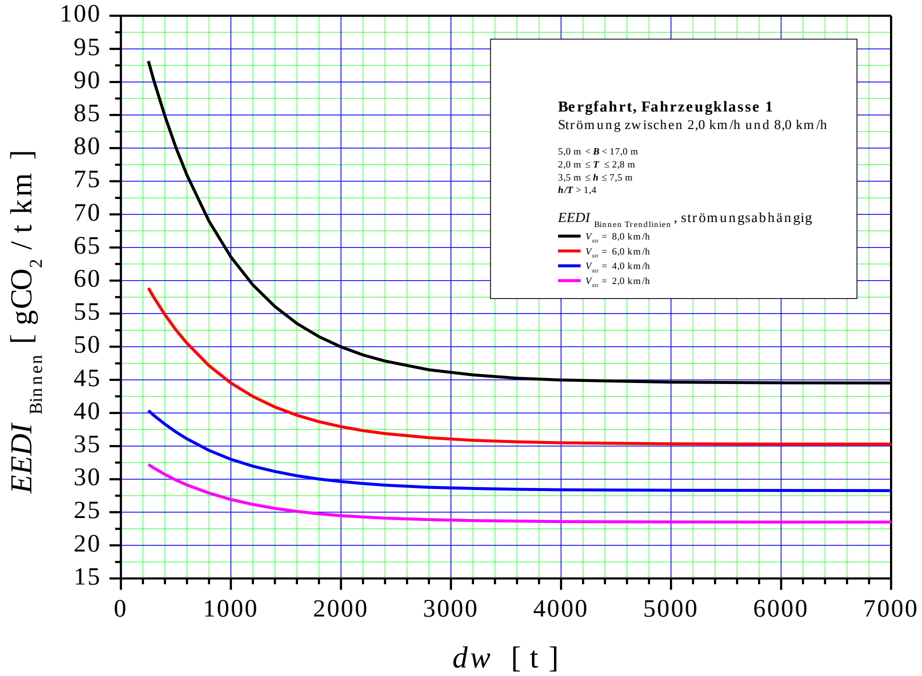

Fig. 2: $EEDI_{Binnen}$ trend lines for vessel class 1 (current-dependent)

5.1.2 Vessel class 2 (tankers)

The following general conditions apply for tankers during the test voyage to determine the $EEDI_{Binnen}$ in an upstream direction:

a) Draught: T = 1.5 · propeller diameter in the range 2.0 m ≤ T ≤ 2.8 m

b) Length: 40.0 m ≤ L ≤ 135.0 m

c) Width: 5.0 m ≤ B ≤ 17.0 m

d) Deadweight: 250 t ≤ dw ≤ 6000 t

e) Current speed: 2.0 km/h ≤ V_{str} ≤ 8.0 km/h

f) Water depth: 3.5 m ≤ h ≤ 7.5 m

g) Water depths/draught ratio: h/T ≥ 1.40

The shaft power is to be determined using equation (14)

$$P_{\mathrm{D\,Berg\,TMS}} = P_{\mathrm{D\,Berg\,MS}} \quad [\mathrm{kW}] \qquad (14)$$

During the test voyage the current speed must be known and the speed $V_{\text{üG}}$ measured with the shaft power setting $P_{\mathrm{D\,Berg\,MS}}$

The $EEDI_{Binnen}$ is calculated as per equation (3).

$$EEDI_{\mathrm{Binnen}} = \frac{CF \cdot SFC \cdot P_{\mathrm{D\,(vessel\,type)\,(upstream\,or\,downstream\,or\,mean\,value)}}}{V_{\text{ü}G} \cdot dw} \qquad (3)$$

The $EEDI_{Binnen}$ calculated using equation (3) should be smaller than the index calculated using equation (15) and accordingly fall below the current-dependent $EEDI_{Binnen}$ trend line in Fig. 3 .

$$EEDI_{\ TMS\ upstream\ trendline} =$$

$$(\alpha_8 + \beta_6 \cdot V_{\mathrm{str}} + \delta_4 \cdot V_{\mathrm{str}}{}^2) + (\gamma_6 + \varepsilon_3 \cdot V_{\mathrm{str}} - \zeta_2 \cdot V_{\mathrm{str}}{}^2 + \eta_2 \cdot V_{\mathrm{str}}3) \cdot EXP\left(\frac{dw}{-\theta_2}\right) \qquad (15)$$

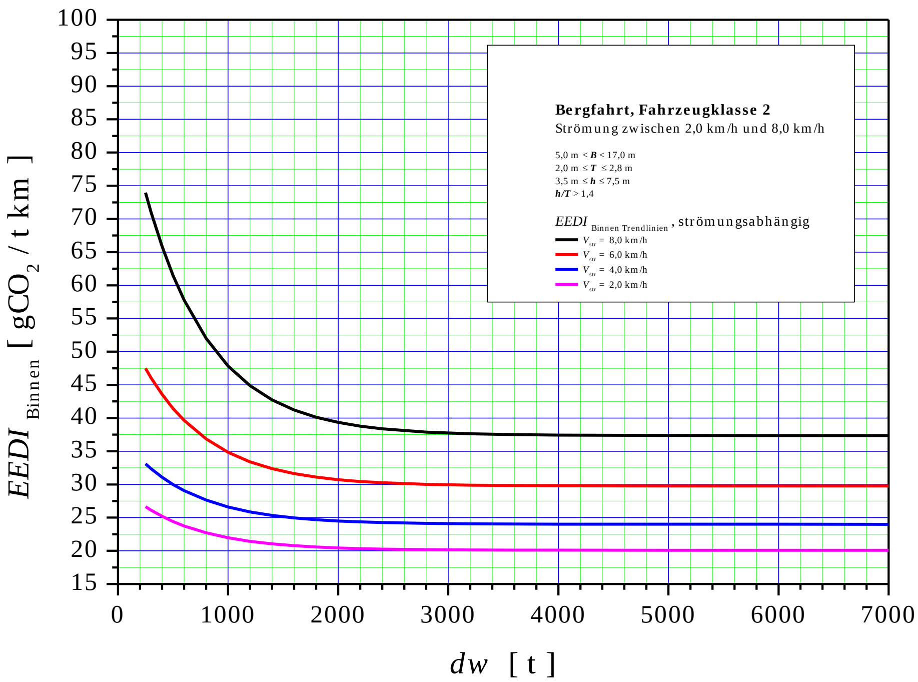

Fig. 3: $EEDI_{Binnen}$ trend lines for vessel class 2 (current-dependent, upstream)

5.1.3 Vessel class 3 (pushed convoys)

Vessel group 3 includes pushed convoys, comprising a pusher and one or more lighters, and pushed convoys comprising a single ship with one, two and three lighters. 3-abreast/single-unit pushed formations cannot be considered.

a) Draught: T = 1.5 · propeller diameter in the range 2.0 m ≤ T ≤ 3.0 m

b) Length (lighter formation only): 76.5 m ≤ L ≤ 230.0 m

c) Width: 9.0 m ≤ B ≤ 34.4 m

d) Deadweight: 500 t ≤ dw ≤ 18000 t

e) Current speed: 2.0 km/h ≤ V_{str} ≤ 6.0 km/h

f) Water depth: 3.5 m ≤ h ≤ 7.5 m

g) Water depths/draught ratio: h/T ≥ 2.0

The shaft power is to be determined using equation (16)

$$P_{\mathrm{D\ Berg\ SV}} = \left(\alpha_9 + \beta_7 \cdot EXP(-\gamma_4 \cdot B) - \delta_5 \cdot EXP\left(\frac{\boldsymbol{h}}{-\varepsilon 4}\right)\right) \cdot dw \quad [\mathrm{kW}] \qquad (16)$$

During the test voyage the current speed must be known and the speed $V_{üG}$ measured with the shaft power setting. The $EEDI_{Binnen}$ is calculated as per equation (3).

$$EEDI_{\mathrm{Binnen}} = \frac{CF \cdot SFC \cdot P_{\mathrm{D\ (vessel\ type)\ (upstream\ or\ downstream\ or\ mean\ value)}}}{V_{üG} \cdot dw} \qquad (3)$$

The $EEDI_{Binnen}$ calculated using equation (3) should be smaller than the index calculated using equation (17) and accordingly fall below the current-dependent $EEDI_{Binnen}$ trend line in Fig. 4 .

$$EEDI_{SV\ Berg\ trendline} =$$
$$(\alpha_8 - \beta_8 \cdot V_{str} + \delta_6 \cdot V_{str}^2) + (\gamma_7 + \varepsilon_5 \cdot V_{str} + \zeta_3 \cdot V_{str}^2) \cdot EXP\ (dw/{-\eta_3}) \qquad (17)$$

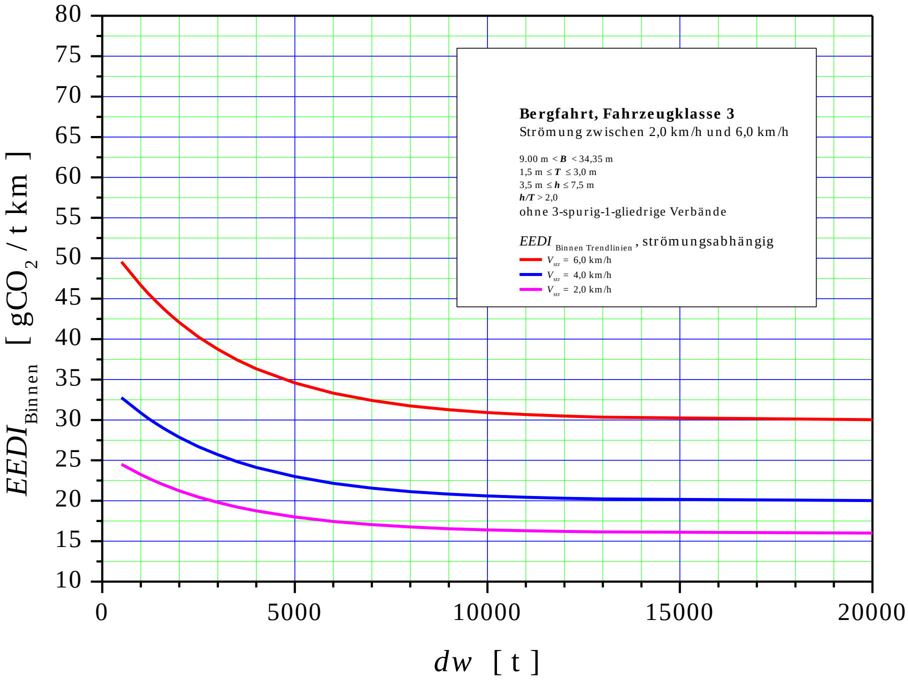

Fig. 4: $EEDI_{Binnen}$ trend lines for vessel class 3 (current-dependent, upstream)

5.1.4 Vessel class 4 (passenger vessels)

The following general conditions apply for passenger vessels during the test voyage to determine the $EEDI_{Binnen}$ in an upstream direction:

a) Draught: 0.6 m ≤ T ≤ 2.1 m

b) Length: 26.0 m ≤ L ≤ 135.0 m

c) Width: 5.0 m ≤ B ≤ 14.0 m

d) Displacement: 50 t ≤ Δ ≤ 3000 t

e) Current speed: 2.0 km/h ≤ V_{str} ≤ 6.0 km/h

f) Water depth: 3.5 m ≤ h ≤ 7.5 m

g) Water depths/draught ratio: h/T ≥ 1.40

The shaft power is to be determined using equation (18)

$$P_{\text{D Berg PV}} = (\alpha_{10} + \beta_9 \cdot EXP(-\gamma_4 \cdot B) - \varepsilon_6 \cdot EXP\left(\frac{h}{-\zeta_4}\right)) \cdot \Delta \quad \text{[kW]} \qquad (18)$$

During the test voyage the current speed must be known

and the speed $V_{\text{üG}}$ measured with the shaft power setting. $EEDI_{\text{Binnen}}$ is calculated as per equation (4).

$$EEDI_{\text{Binnen}} = \frac{CF \cdot SFC \cdot P_{\text{D (vessel type) (upstream or downstream or mean value)}}}{V_{\text{ü}G} \cdot \Delta} \qquad (4)$$

The $EEDI_{Binnen}$ calculated using equation (4) should be smaller than the index calculated using equation (19) and accordingly be read off from below the current-dependent $EEDI_{Binnen}$ trend line in Fig. 5.

$$EEDI_{\text{PV Berg trendline}} =$$
$$(\alpha_{11} + \beta_{10} \cdot V_{str} + \gamma_8 \cdot V_{str}^2) + (\delta_7 - \varepsilon_7 \cdot V_{str} + \zeta_5 \cdot V_{str}^2) \cdot EXP\ (\Delta/-\eta_4) \qquad (19)$$

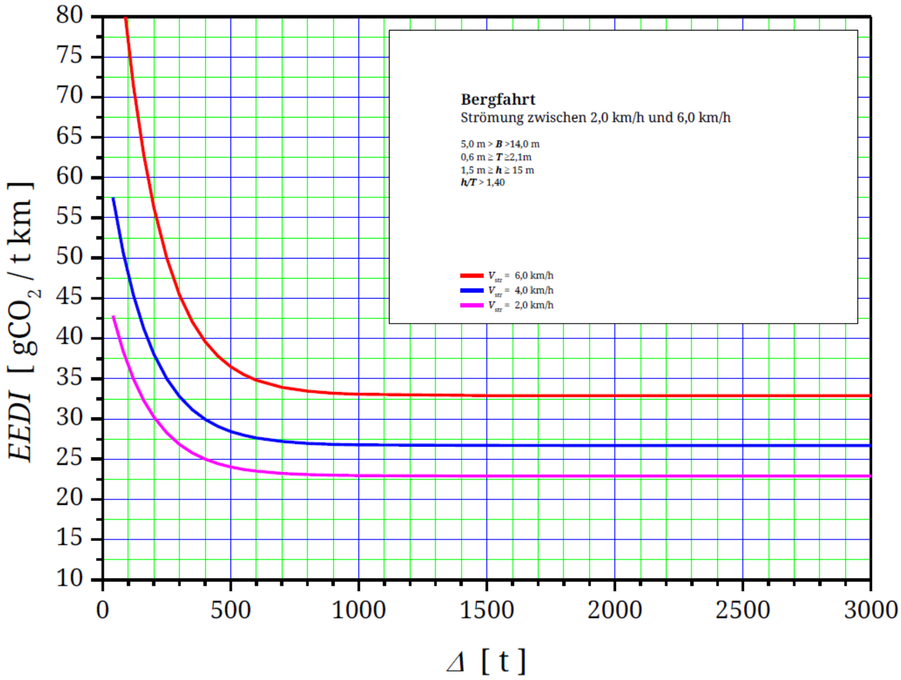

Fig. 5: $EEDI_{Binnen}$ trend lines for vessel class 4 (current-dependent, upstream)

5.2 Zone 4 waterways

The canal cross-section with its standardised trapezoidal canal profile is defined as being representative for zone 4 waterways.

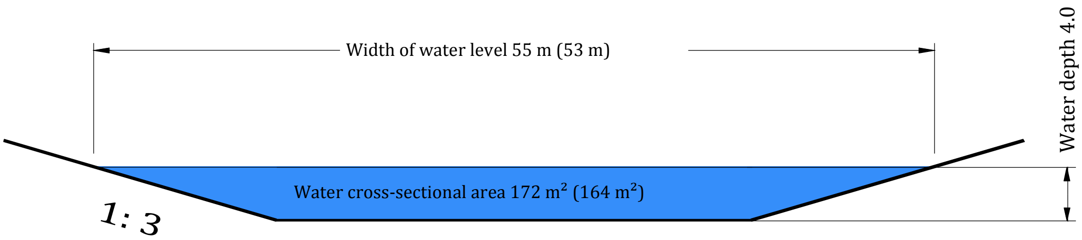

Fig. 6: Canal with trapezoidal cross-section

This canal cross-section, with minor dimensional variances, is common within zone 4 waterways, for example large stretches of the Mittelland Canal, the Dortmund-Ems Canal, the Elbe-Havel Canal, the Elbe-Seiten Canal and the Main-Danube Canal. These canals are navigable with a draught of 2.5 m or 2.8 m. Adjoining or crossing rivers and canals may exhibit slightly differing water depths, thus reducing the usable draughts. Therefore the choice of draught for the test voyage in the trapezoidal profile canal will be dependent on a multiple of the propeller diameter with a maximum upper limit. This restriction applies for dry cargo vessels, container ships, tankers and pushed convoys. The design draught will be used for passenger vessels.

5.2.1 Vessel class 1 and 2 (dry cargo vessels, container ships and tankers)

The following general conditions apply for dry cargo vessels, container ships and tankers during the test voyage to determine the $EEDI_{\text{Binnen}}$ in a standard trapezoidal profile canal:

a) Draught: T = 1.7 · Propeller diameter but not exceeding T = 2,5 m

b) Speed over the ground:

$V_{\text{üG}}$ = 10.0 km/h for vessels with a width of B < 11.0 m

$V_{\text{üG}}$ = 9.4 km/h for vessels with a width of B < 11.0 m

The required shaft power is measured at the appropriate speed. The $EEDI_{\text{Binnen}}$ is determined as per equation (3).

$$EEDI_{\text{Binnen}} = \frac{CF \cdot SFC \cdot P_{\text{D (vessel type) (upstream or downstream or mean value)}}}{V_{\text{ü}G} \cdot dw} \qquad (3)$$

The calculated $EEDI_{\text{Binnen}}$ shall be smaller than the one calculated as per the equation (20).

$$EEDI_{MS\ Kanal\ trendline} = \alpha_{12} - \beta_{11} \cdot dw \qquad (20)$$

5.2.2 Vessel class 3 (pushed convoys)

The following general conditions apply for pushed convoys during the test voyage to determine the $EEDI_{\text{Binnen}}$ in a standard trapezoidal profile canal:

a) Draught: 1.7 · Propeller diameter but not exceeding T = 2.5 m

b) Speed over the ground:

$V_{\text{üG}}$ = 10.0 km/h for convoys with a width of B < 11.0 m

$V_{\text{üG}}$ = 9.4 km/h for convoys with a width of B ≥ 11.0 m

The shaft power is measured at the appropriate speed. The $EEDI_{\text{Binnen}}$ is determined as per equation (3).

$$EEDI_{\text{Binnen}} = \frac{CF \cdot SFC \cdot P_{\text{D (vessel type) (upstream or downstream or mean value)}}}{V_{\text{ü}G} \cdot dw} \qquad (3)$$

The calculated $EEDI_{\text{Binnen}}$ shall be smaller than the one calculated as per the equation (21).

$$EEDI_{SV\ Kanal\ trendline} = \alpha_{13} - \beta_{12} \cdot dw \qquad (21)$$

5.2.3 Vessel class 4 (passenger vessels)

The following general conditions apply for passenger vessels during the test voyage to determine the $EEDI_{\mathrm{Binnen}}$ in a standard trapezoidal profile canal:

a) Draught: identical with the design draught, but not exceeding T = 2.5 m

b) Speed over the ground:

$V_{\mathrm{üG}}$ = 10.0 km/h for passenger vessels with a width of B < 11.0 m

$V_{\mathrm{üG}}$ = 9.4 km/h for passenger vessels with a width of $B \geq$ 11.0 m

The shaft power is measured at the appropriate speed. The $EEDI_{\mathrm{Binnen}}$ is determined as per equation (4).

$$EEDI_{\mathrm{Binnen}} = \frac{CF \cdot SFC \cdot P_{\mathrm{D\ (vessel\ type)\ (upstream\ or\ downstream\ or\ mean\ value)}}}{V_{\mathrm{ü}G} \cdot \Delta} \qquad (4)$$

It was not possible to calculate an upper $EEDI_{\mathrm{FGS\ Kanal}}$ trend line as no model and field studies are available. An initial indication could be the $EEDI_{\mathrm{MS\ Kanal}}$ trend line (20). Displacement mass rather than deadweight is to be used for passenger vessels, as per equation (22).

$$EEDI_{FGS\ canal\ trendline} = \alpha_{14} - \beta_{13} \cdot \Delta \qquad (22)$$

6 *EEDI* s for stepwise evaluation

6.1 Stepwise evaluation for the general *EEDI*$_{\text{Binnen}}$

6.1.1 Vessel class 1 - 3

The analysis in Chapter 6 Large-scale trials in the main report is used to estimate a realistic gradation of the *EEDI*$_{\text{Binnen}}$ as regards reducing CO_2 emissions. The following Fig. 7 shows the upper envelope curve (*EEDI*$_{\text{Trendlinie}}$), delimiting the large-scale test data and the associated data points. Fig. 7 also features two additional curves plotting CO_2 emissions reduced by 15% (red curve) and by 25% (green curve) relative to the *EEDI*$_{\text{Trendlinie}}$ (baseline). In a first approximation, the green curve can be seen as the lower envelope curve of the large-scale test data. That means that there are ships in the existing fleet that emit up to 25 % less CO_2 relative to the *EEDI*$_{\text{Trendlinie}}$ (baseline). For new ships, the gradations could indicate a future reduction in CO_2 emissions. For the existing fleet, an absolute reduction in CO_2 emissions of between 15% and 25% is only possible with extensive conversion measures, such as changing the shape of the vessel's stern and/or fore-section, optimising the propulsion and steering system and/or increasing the vessel's length.

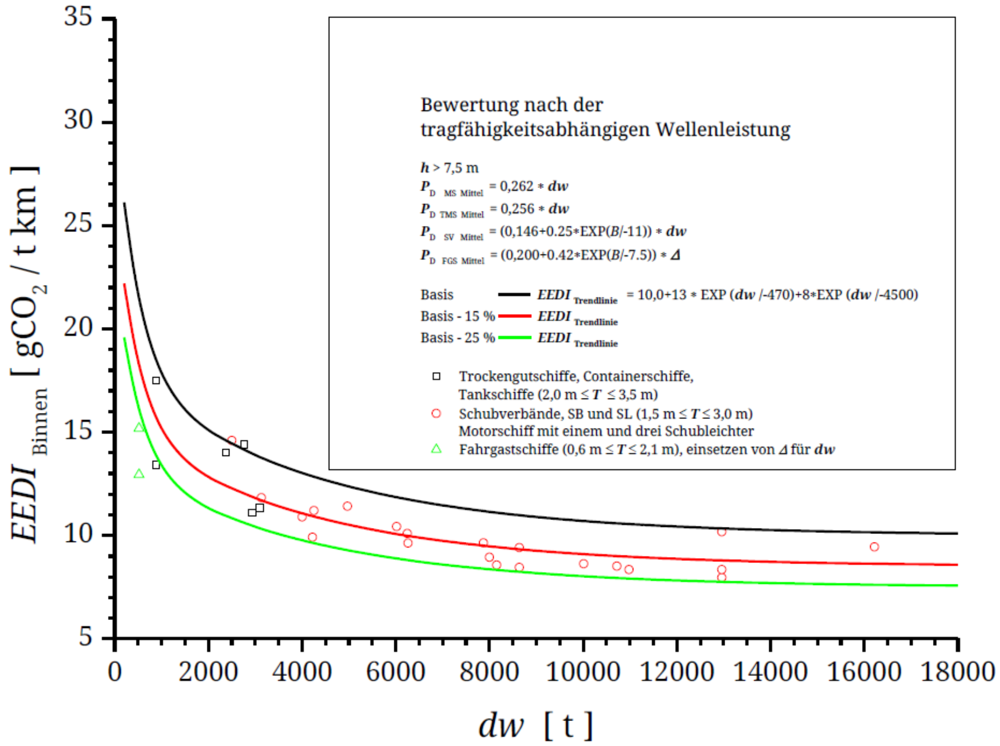

Fig. 7: Stepwise evaluation of the general EEDI$_{\text{Binnen}}$ (based on shaft power as a function of deadweight)

The $EEDI_{\text{Trendlinien (trendlines)}}$ for a reduction in CO_2 emissions of between 15% and 25% can be expressed in conjunction with the equation (9).

Baseline: $$EEDI_{\text{trendline}} = \alpha_4 + \beta_2 \cdot EXP\left(\frac{dw}{-\gamma_2}\right) + \vartheta 1 \cdot EXP\left(\frac{dw}{-\delta 1}\right) \quad (9)$$

Baseline -15 %: $$EEDI_{\text{trendline}} = \left[\alpha_4 + \beta_2 \cdot EXP\left(\frac{dw}{-\gamma_2}\right) + \vartheta 1 \cdot EXP\left(\frac{dw}{-\delta 1}\right)\right] \cdot 0{,}85 \quad (23)$$

Baseline -25 %: $$EEDI_{\text{trendline}} = \left[\alpha_4 + \beta_2 \cdot EXP\left(\frac{dw}{-\gamma_2}\right) + \vartheta 1 \cdot EXP\left(\frac{dw}{-\delta 1}\right)\right] \cdot 0{,}75 \quad (24)$$

6.1.2 Vessel class 4

The $EEDI_{\text{Trendlinien}}$ for a possible reduction in CO_2 emissions of between 15% and 25% can be expressed in conjunction with equation (11).

Baseline: $$EEDI_{\text{trendline}} = \alpha_4 + \beta_2 \cdot EXP\left(\frac{\Delta}{-\gamma_2}\right) + \vartheta 1 \cdot EXP\left(\frac{\Delta}{-\delta 1}\right) \quad (11)$$

Baseline -15 %: $$EEDI_{\text{trendline}} = \left[\alpha_4 + \beta_2 \cdot EXP\left(\frac{\Delta}{-\gamma_2}\right) + \vartheta 1 \cdot EXP\left(\frac{\Delta}{-\delta 1}\right)\right] \cdot 0{,}85 \quad (25)$$

Baseline -25 %: $$EEDI_{\text{trendline}} = \left[\alpha_4 + \beta_2 \cdot EXP\left(\frac{\Delta}{-\gamma_2}\right) + \vartheta 1 \cdot EXP\left(\frac{\Delta}{-\delta_1}\right)\right] \cdot 0{,}75 \quad (26)$$

6.2 Stepwise evaluation of the navigation area-dependent *EEDI*Binnen, zone 3 (Rhine)

6.2.1 Vessel class 1 (dry cargo vessels and container ships)

For vessel class 1, the comparison of the results of the large-scale trials with those of the model tests shows that the findings of the large-scale trials have resulted in an adjustment to the upper envelope curves. The spread in the large-scale trial data permits a gradation of between 15% and 25%. Fig. 8 illustrates the relationships at a current speed of 6.0 km/h (black curve baseline: $EEDI_{\text{ Trendlinie}}$ at a current speed of 6.0 km/h).

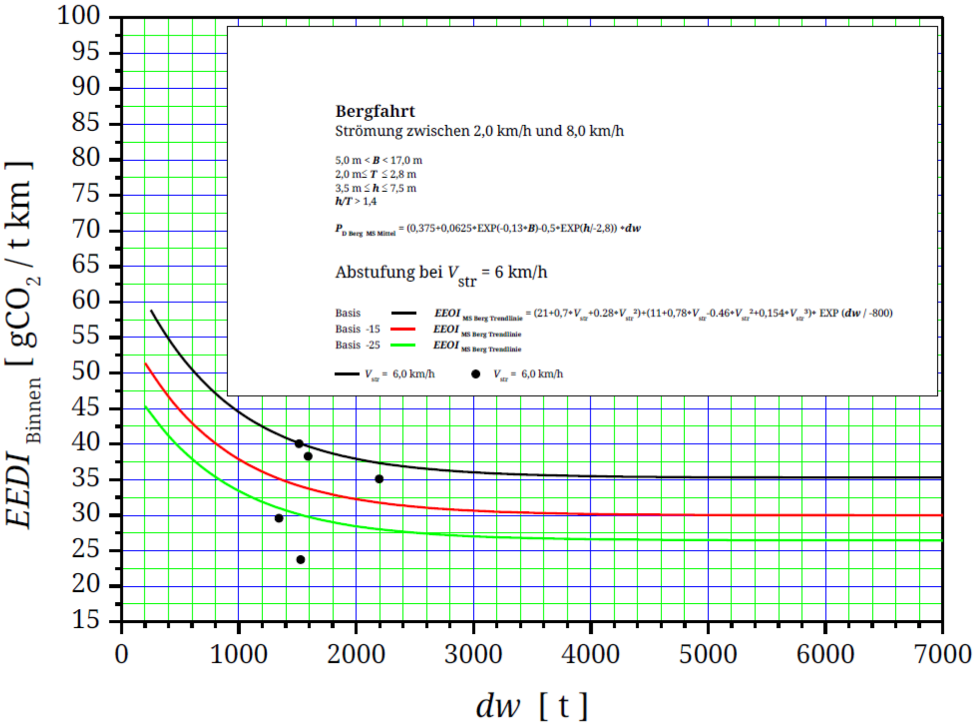

Fig. 8: Stepwise evaluation of the navigation area-dependent $EEDI_{Binnen}$

The green curve (green curve baseline -25%: $EEDI_{Trendlinie}$ at a current speed of 6.0 km/h) does not show the lower envelope curve, there are two large-scale test measurement data points below the green curve, such that vessels in the existing fleet achieve a minimum of 25% lower CO_2- emissions relative to the $EEDI_{Trendlinie}$ (baseline). With the exception of one data point at a current speed of 8.0 km/h there are no further large-scale test measurements, resulting in the assumption, as a first approximation for all current speeds between 2.0 km/h and 8.0 km/h, that a 25% reduction in CO_2 emissions relative to the $EEDI_{Trendlinie}$ (baseline) is considered possible for new ships.

Accordingly, for new ships, the $EEDI_{Trendlinien}$ for a possible reduction in CO_2 emissions of between 15% and 25% could be expressed in conjunction with equation (13) for current speeds between 2.0 km/h and 8.0 km/h. Modification of vessels in the existing fleet, having regard to the extensive conversion measures in 6.1.1, is conceivable.

Baseline:

$EEDI_{\text{MS Berg trendline}} =$

$$(\alpha_7 + \beta_5 \cdot V_{str} + \gamma_5 \cdot V_{str}^2) + (\delta_3 + \varepsilon_2 \cdot V_{str} - \zeta_1 \cdot V_{str}^2 + \eta_1 \cdot V_{str}^3) \cdot EXP\left(\frac{dw}{-\theta 1}\right) \qquad (13)$$

Baseline -15 %:

$EEDI_{\text{MS Berg trendline}} =$

$$(\alpha_7 + \beta_5 \cdot V_{str} + \gamma_5 \cdot V_{str}^2) + (\delta_3 + \varepsilon_2 \cdot V_{str} - \zeta_1 \cdot V_{str}^2 + \eta_1 \cdot V_{str}^3) \cdot EXP\left(\frac{dw}{-\theta 1}\right) \cdot 0{,}85 \qquad (27)$$

Baseline -25 %:

$EEDI_{\text{MS Berg trendline}} =$

$$(\alpha_7 + \beta_5 \cdot V_{str} + \gamma_5 \cdot V_{str}^2) + (\delta_3 + \varepsilon_2 \cdot V_{str} - \zeta_1 \cdot V_{str}^2 + \eta_1 \cdot V_{str}^3) \cdot EXP\left(\frac{dw}{-\theta 1}\right) \cdot 0{,}75 \qquad (28)$$

6.2.2 Vessel class 2 (tankers)

Only two data points from large-scale trial measurements were available for vessel class 2 (tankers) for comparison with the model test results. Owing to the limited comparability for vessel class 2 it is not proposed that there be an gradation to reduce CO_2 emissions.

6.2.3 Vessel class 3 (pushed convoys)

For vessel class 3 (pushed convoys) it is apparent that at a current speed of 6.0 km/h, the existing fleet's convoys are capable, at a minimum, of 25% lower CO_2 emissions relative to the$EEDI_{\text{Trendlinie}}$ (baseline). It is therefore proposed that there be a gradation in CO_2 emissions of 15% and 25% for new ships based on the $EEDI_{\text{ Trendlinie}}$, equation (17) for current speeds between 2.0 km/h and 6.0 km/h.

Baseline:

$$EEDI_{\text{SV Berg trendline}} = (\alpha_8 - \beta_8 \cdot V_{\text{str}} + \delta_6 \cdot V_{\text{str}}^2) + (\gamma_7 + \varepsilon_5 \cdot V_{\text{str}} + \zeta_3 \cdot V_{\text{str}}^2) \cdot EXP\ (dw/-\eta_3) \tag{17}$$

Baseline -15 %:

$$EEDI_{\text{SV Berg trendline}} = (\alpha_8 - \beta_8 \cdot V_{\text{str}} + \delta_6 \cdot V_{\text{str}}^2) + (\gamma_7 + \varepsilon_5 \cdot V_{\text{str}} + \zeta_3 \cdot V_{\text{str}}^2) \cdot EXP\ (dw/-\eta_3) \cdot 0{,}85 \tag{29}$$

Baseline -25 %:

$$EEDI_{\text{SV Berg trendline}} = (\alpha_8 - \beta_8 \cdot V_{\text{str}} + \delta_6 \cdot V_{\text{str}}^2) + (\gamma_7 + \varepsilon_5 \cdot V_{\text{str}} + \zeta_3 \cdot V_{\text{str}}^2) \cdot EXP\ (dw/-\eta_3) \cdot 0{,}75 \tag{30}$$

6.2.4 Vessel class 4 (passenger vessels)

Only two data points from large-scale trial measurements were available for vessel class 4 (passenger vessels) for comparison with the model test results. Owing to the limited comparability for vessel class 4 it is not proposed that there be a gradation to reduce CO_2 emissions.

6.3 Stepwise evaluation of the navigation area-dependent $\mathbf{EEDI_{Binnen}}$, zone 4

CO_2 emissions by existing vessels within zone 4 is approximately 1.5 to 3.5 times lower than within zone 3. The proposal for new ships is only to apply a 15% gradation until comprehensive large-scale tests have confirmed or modified the baseline $EEDI_{\text{Kanal Trendlinien}}$

6.3.1 Vessel class 1 (dry cargo vessels and container ships)

Baseline: $EEDI_{\text{MS Kanal trendline}} = \alpha_{12} - \beta_{11} \cdot dw$ (20)

Baseline -15%: $EEDI_{\text{MS Kanal trendline}} = \alpha_{12} - \beta_{11} \cdot dw \cdot 0{,}85$ (31)

6.3.2 Vessel class 2 (tankers)

Baseline: $EEDI_{\text{TMS Kanal trendline}} = \alpha_{12} - \beta_{11} \cdot dw$ (21)

Baseline -15%: $EEDI_{\text{TMS Kanal trendline}} = \alpha_{12} - \beta_{11} \cdot dw \cdot 0{,}85$ (32)

6.3.3 Vessel class 3 (pushed convoys)

Baseline: $EEDI_{\text{SV Kanal trendline}} = \alpha_{13} - \beta_{12} \cdot dw$ (22)

Baseline -15%: $EEDI_{\text{SV Kanal trendline}} = \alpha_{13} - \beta_{12} \cdot dw \cdot 0{,}85$ (33)

6.3.4 Vessel class 4 (passenger vessels)

Baseline: $EEDI_{\text{FGS Kanal trendline}} = \alpha_{14} - \beta_{13} \cdot \Delta$ (23)

Baseline -15%: $EEDI_{\text{FGV Kanal trendline}} = (\alpha_{14} - \beta_{13} \cdot \Delta) \cdot 0{,}85$ (34)

7 *EEOI* in inland navigation

7.1 Influence of environmental conditions

The energy requirement involved in operating inland vessels is essentially influenced by navigable channels that restrict width and depth with periodically changing water conditions and current speeds. The same transport conditions are seldom encountered on successive days, making it difficult or impossible to identify an individual factor influencing fuel consumption.

7.2 Proposal for capturing the *EEOI*

The first step is to propose adopting the same approach as for maritime navigation, see equation (2). Maritime navigation is subject to similar difficulties as a result of the influence of wind and waves.

It is proposed that an energy assessment be conducted for inland vessels for individual sections of a transport movement or journey. Available sections on the Rhine are the stretches between the mouths of the navigable tributaries or canals. The Moselle, Main and Neckar can also be a section. A possible sub-area within the West German canal area would be the link from the Rhine to Berlin or Lauenburg. The Ems, Weser, Elbe and the German Danube also provide possible sections.

In practice, the input data for an inland navigation *EEOI* is already largely recorded for every vessel. Total fuel consumption is determined by means of fuel tank level indicators at the beginning and end of a transport movement and reconciled with bunker quantities. Information on the relevant bunkering qualities is required to be carried on board and is.

Admittedly, the indicated fuel quantity is not typically captured and recorded upon entry into a different area of navigation, for example when passing from the Rhine into the Main. The water conditions and/or associated water levels are also not typically recorded with the fuel consumption data.

But it is only by amalgamating this data that it is possible to determine, for comparable vessel and fairway conditions, whether a particular nautical strategy, a change in the way the vessel is operated, a structural change to the vessel or the water conditions on the fairway have resulted in a change in energy performance for better or for worse. Determining a change in energy performance requires the data that has already been gathered to be organised such that comparable conditions can be compared.

The approach to evaluating energy efficiency in operating the vessel might be as follows:

The fuel consumption readings at the respective river or canal mouths or confluences are determined and calculated as per equation (2). This involves use of the distance *D* in km. The representative water level of a section and whether the journey is upstream or downstream are recorded.

Fuel consumption for travel without a cargo can be documented separately and is taken into consideration within a specific timeframe.

An *EEOI* specific to a particular section and as a function of water level can thus be calculated, permitting energy requirement comparisons. The viability of this method depends in practice on how accurately fuel consumption can be established using the fuel level indicators. This will also determine how long a section needs to be, or which differences in fuel quantities are readable with sufficient accuracy to yield good fuel consumption results for the stretch of water in question. Regularly documenting energy consumption data in a database will in the medium term allow appropriate comparisons to be made and thus conclusions drawn.

This method of capturing CO_2 emissions per deadweight (displacement mass) and distance takes account of total transport movement fuel consumption as a function of navigation area. Provided that fuel level indicators are available no additional measuring equipment is required. This method can therefore be applied with the existing on-board equipment and thus lends itself to determining the energy rating of the existing fleet. Relatively long test sections should be selected that are regularly used by the vessels in question.

Fig. 9 illustrates in the form of an Excel table how an *EEOI* could be calculated and documented.

	Example:	***EEOI*** in inland navigation															
	Section	III	IV	V	VI	VII	VIII	IIIa	IVa	IVb	Va	VIa	A	B	C	D	
	Sections	Spyck-Koblenz	Koblenz-Mainz	Mainz-Mannheim	Mannheim-Iffezheim	Iffezheim-Kembs	Kembs-Rheinfelden	Mosell e	Main	MDK	Danube	Neckar	WDK, RHK, DEK, MLK, ESK, EHK,	Ems	Weser	Elbe	**Total**
	Section length	266 km	93 km	74 km	91 km	160 km	30 km										
	Gauge station	Cologne	Kaub	Mannheim	Maxau		Rheinhalle										
1	***Journey***	Duisburg to Bamberg						***Amount of cargo***		2000	t						
	Water level [cm]	**314**	**209**														
	Distance [km]	189	93						387								669
	Consumption [l]	3732	2542						5290								11564
	EEOI $_i$ [gCO_2/tkm]	26.7	37.0						18.5								23.4
	Travel without cargo	Bamberg to Regensburg															
	Consumption [l]																1400
2	***Journey***	Regensburg to Berlin						***Amount of cargo***		1500	t						
	Water level	**305**	**199**														
	Distance [km]	282							378	204			587				1451
	Consumption [l]	1300							3360	1896			5933				12489
	EEOI $_i$ [gCO_2/tkm]	8.3							16.1	16.8			18.3				15.5
	Travel without cargo	none															
	Consumption [l]																
3	***Journey***	Berlin to Duisburg						***Amount of cargo***		1800	t						
	Water level																
	Distance [km]												587				587
	Consumption [l]												6215				6215
	EEOI $_i$ [gCO_2/tkm]												15.9				15.9
	Travel without cargo	none															
	Consumption [l]																
4	***Journey***	Duisburg to Wörth						***Amount of cargo***		2200	t						
	Water level	**325**	**220**	**255**	**449**												
	Distance [km]	189	93	74	59												415
	Consumption [l]	4050	2750	1800	1550												10150
	EEOI $_i$ [gCO_2/tkm]	26.4	36.4	30.0	32.4												30.1
	Travel without cargo	none															
	Consumption [l]																
										Amount of cargo t			7500				
										Distance [km]			3121				
										Consumption [l]			41817				
										EEOI $_i$ [gCO_2/tkm]			19.25				

Fig. 9: Model evaluation sheet for calculating an *EEOI* in inland navigation.