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Environmental impacts of steel ship hulls building and recycling by life cycle assessment (LCA)

Mehmet Önal[a], Gökdeniz Neşer [b] and K. Turgut Gürsel[b]

[a]Sakarya University of Applied Sciences, Maritime Higher Vocational School, Sakarya, Turkey; [b]Dokuz Eylül University Institute of Marine Sciences and Technology, Izmir, Turkey

ABSTRACT

Serious environmental impacts of a ship's life cycle occur during building and end-of life phases. In this study, data gathered from the related sites in Turkey for steel hull building and its reverse process of steel hull recycling phases for different type of ships have been assessed by using SimaPro 8.2.3 software and CML-IA methodology to determine impact categories of abiotic depletions, acidification, eutrophication, global warming, ozone depletion, human toxicity, freshwater and marine aquatic ecotoxicities, terrestrial ecotoxicity and photochemical oxidation. Results from life cycle inventories and impact assessment have shown that 85% of the related impacts caused by shipbuilding and the complexity of the ship type have significant effects on these impacts. The paper has also shown that LCA is a valuable tool which can help stakeholders for a sustainable industries.

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1. Introduction

Based on extensive evidence, human activities, especially emissions of greenhouse gases, are the cause of the warming since the mid-twentieth century. In addition to warming, global climate is changing by resulting in increasing surface, atmospheric and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea level; ocean acidification and increasing atmospheric water vapour (Wuebbles et al. 2017). Shipping sector, as one of the serious sources of the related emissions, has gathered momentum for contributing to the efforts of mitigation goals of limiting the mentioned adverse effects of climate changes (Gilbert and Bows 2012; Gilbert et al. 2018). For this purpose, the International Maritime Organization (IMO) implemented modifications to its MARPOL convention's Annex VI on air pollutions measures by adopting the energy efficiency design index (EEDI) and the ship energy efficiency management plan (SEEMP) (MEPC 2009). However, not only the environmental impacts during the operation phase of a ship, but also these impacts of its building and recycling (end-of-life) phases should be considered to understand the total load of shipping industry on the environment.

According to the study of Andersen et al. (2001) that focused on tankers and bulker ships, almost 75% of material streams of a ship in LDT (Light Displacement Ton) are composed of ferrous scrap, namely steel. Similar studies carried out by sampling data during the recycling phase of the ships show that amounts of steel vary from 56% of LDT for general cargo to 85% of LDT for oil tanker (Hess et al. 2001; Demaria 2010; Adak 2013; Sujauddin et al. 2014).

It has been shown that in the study of Ko and Gantner (2016), the environmental impact per created added value is high for the production phase (its share in the life cycle is between 24.6 and 47.5%) and especially for the end-of-life phase (its share in the life cycle is over 50%). As for use or operating phase, it endures very little to almost none environmental impact per created added value.

Because of higher environmental impact, in this study, shipbuilding and ship recycling phases of a ship, as a main tool in the marine industry, have been considered. In these phases, mainly steel processes such as cutting, joining and forming are prominent. Steel is not only at the core of today's shipbuilding industry, but also everywhere in the modern civilisation and at the heart of sustainable future (Broadbent 2016).

Chatzinikolaou and Ventikos (2014) benefited from life cycle approach to determine environmental impacts of air emissions of shipping activities. They studied on a Panamax tanker as a system with two subsystems: hull and machinery. They found that steel production process is responsible nearly 90% of the total CO2 emissions and large quantities of CO, PM and NOX emissions in shipbuilding. It is followed by the impacts of transport of materials, coating, cutting, welding, anodes and abrasive blasting processes. The authors also underlined that hull subsystem's environmental impacts are fairly distributed in three life cycle phases: shipbuilding has a share of 40% of total impacts, while maintenance and recycling phase are responsible for 35 and 25%, respectively.

In Fet's (2002) study, assuming 95% of all steel was recycled after ended life time, it was found that the ship gives the main contribution to most of the environmental impact categories such as greenhouse gases, acidification, photo-oxidant formation, eutrophication and smog formation. The

CONTACT Gökdeniz Neşer gokdeniz.neser@deu.edu.tr Dokuz Eylul University Institute of Marine Sciences and Technology, Baku Blv. 32, Inciralti, Balcova, 35340 Izmir, Turkey

contribution to ozone depletion is mainly from the building phase, while recycling of materials reduces the impact from raw materials significantly, approximately by 80%.

In another study of the same author (Fet 1998), LCA is suggested as a strategic tool for policy- and decision-making, a tool for highlighting important connection between materials, environment and costs throughout the life cycle of a ship. For Fet, however, the lack of information on ship recycling activities in the world makes difficult attempts for integrated approach to the maritime industries' environmental impact. The same complaints about the lack of reliable data are underlined in the report of OECD Council Working Party on Shipbuilding (WP6) entitled 'Environmental and Climate Change Issues in the Shipbuilding Industry' (OECD 2010). In the report, the resistance from the various maritime sectors (shipbuilding, ship operators and ship recyclers) to deal with ships through 'life-cycle' thinking is stressed, although this approach is almost the most effective way of minimising the environmental impacts of a ship throughout its life and strongly recommended by the Council. Steel production being the world's one of the most energy-intensive processes is identified as the source of a number of environmental concerns in the report. The ways of decreasing negative impacts of this process using improved steels such as ultra-light and high-strength steel is proposed. Additionally, surface treatment operations such as abrasive blasting, coating, painting (especially with antifoulings), ship repair and maintenance processes with their potential pollutions such as oil spillage have been pointed out in this very detailed report to achieve a sustainable growth (green growth) for the related industries as a whole. The same conclusions were reached in the workshop on 'green technologies in shipbuilding and ship repair industries' organised in the framework of MATES (Maritime Alliance for Fostering the European Blue Economy Through a Marine Technology Skilling Strategy) Project funded by EU's Erasmus+ Programme (MATES 2018). The experts drew special attention to the green ship recycling technologies and new shipbuilding materials for their positive impacts on environment in the medium term and long term. The main contribution of our study is to provide reliable data from the field of shipbuilding and ship recycling to support such kind of attempts.

Data collected from the shipyards in the Tuzla (Istanbul) and Yalova Shipbuilding Zones and ship recycling facilities in Aliağa (Izmir) for different type of ships (fishing boat, barge, tug boat, service boat, bulk cargo, tanker, passenger vessel and recreational vessel) have been used in the life cycle assessment model. From the model, life cycle inventory and impact analysis have been carried on and the results are concluded by comparing in terms of ship types and the related processes (shipbuilding or ship recycling).

2. Methodology

LCA methodology was used to evaluate the environmental impacts of steel ship hulls' life cycle, according to the ISO standards 14040 series (2006).

2.1. Goal and scope definition

The overall goal of the study is to analyse comparatively the environmental impacts of two significant industries in maritime industry, ship building and ship recycling, based on their steel material processes in different types of ships, such as tug, passenger ship, fishing vessel, ferry, workboat, barge, bulk carrier and recreational vessels. Ten impact categories have been evaluated by LCA methodology and using the SimaPro 8 software.

LCA methodology has been applied to support implementation of shipbuilding and ship recycling industry and to increase the awareness of decision makers, managers, ship owner, the other stakeholders in these industry at least while selecting the technologies which they need. This study was focused on steel processes such as cutting, forming and joining.

2.2. Functional unit

According to the definition of ISO 14040, the functional unit is 'the quantified performance of a product system for use as a reference unit in a life cycle assessment study' (ISO 14040, 2006). For this study, the functional unit has been assigned as 'a ship' of its kind built in the in the Tuzla Shipyards Zone, Istanbul, Turkey, and recycled in the Aliağa Ship Recycling Zone, İzmir, Turkey during 2008–2018.

2.3. System boundaries

In this study, the system boundaries, defining the processes and inputs and outputs of them, are shown in Figure 1. The processes in this system include:

(1) Shipbuilding process by which steel material is cut and joined by using O_2, CO_2, LPG and electrical energy as the inputs. The outputs of this process are the ship hull and scrap steel materials.
(2) Ship recycling process that ship hull is cut by using O2, LPG, diesel fuel and electrical energy as the inputs and the outputs is scrap steel. Transportation of the scrap steel to steel mills (almost 15 km far from the recycling facilities) is also considered.

Shipbuilding industry of Turkey, as of 2017, has reached to a total capacity of 4.41 million DWT per year with 78 shipyards located mainly in Tuzla (Istanbul) and Yalova (Izmit) (Ministry of Transportation and Infrastructure of Turkey, MTI 2018). Different types of ships given in Table 1 have been built in this industry which needs new approaches of sustainable engineering during material supply and building process.

As the ships have a limited life span of around 20–30 years, it is needed to recycle them for safety issues (Dodds 2007). To operate sustainably, the existing national merchant ship fleet, which has a considerably high age average (Table 2), also need a life cycle assessment approach to predict and to take preventive measures in terms of environmental impacts precisely.

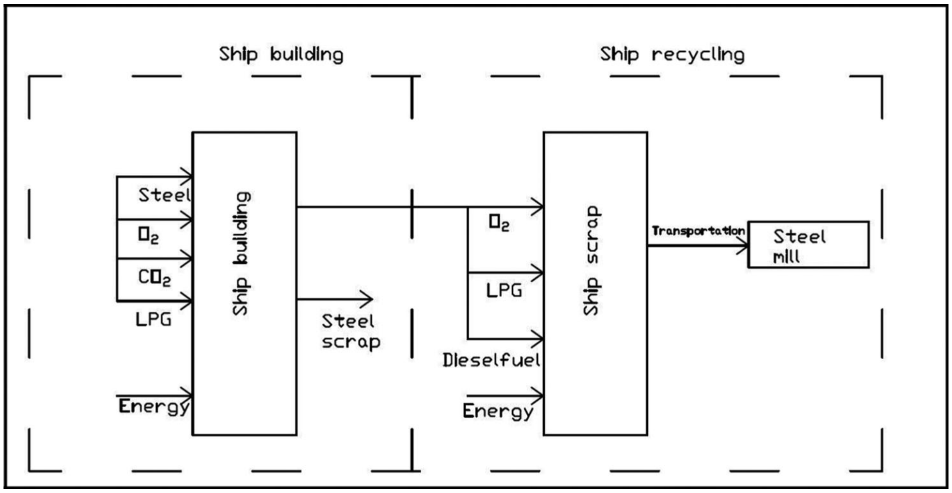

Figure 1. Life cycle system boundaries in the study.

2.4. Data sources and quality

One part of the collected data from interviews and site visits at the shipyard zones in Tuzla (İstanbul) and Yalova and ship recycling zones in Aliağa (İzmir), and the other part of the data provided by the Ministry of Environment and Urbanisation's project coordinated by Kocaeli University, have been used. Data from the facilities are based on the documentations on supply chain management departments and compared with the expert (officers, engineers, managers in the related industry) views.

Data used included amounts of materials such as steel, CO2, O2, LPG and electrical energy during the steel works in the related facilities for different types of ships. The amount of waste steel from these processes is also given by the shipyards.

Steel scrap transportation distance from ship recycling facilities to steel mills is also considered.

Data of steel manufacturing and recycling, the other materials used in steel works, energy and transportation were also obtained from the database included in LCA software used (SimaPro 8). In particular, ecoinvent v2.0 has been used as database for background data (Frischknecht et al. 2007). The sources and the category of data used in this study are listed in Table 3.

3. Results and discussions

3.1. Inventory analysis

For the both processes, inventories of significant environmental flows have been produced. As Neser et al. (2012) carried on a field study in 2009 and 2010 to find the contamination levels of heavy metals (Hg, Cd, Pb, Cr, Cu, Zn, Mn and Ni) along the coast of ship recycling zone at the Çandarlı Bay (Izmir/Turkey). In this study the emissions of these heavy metals in air, water and soil contributing the highest (99%) by mass have been shown in Table 4. The sample ship in this table is a tug boat whose Light Displacement Tonne is 341.7 tonne.

In the study of Neser et al., comparison of metal concentrations with average shale and Mediterranean background

Table 1. Merchant fleet composition of Turkey (MTI 2018).

Ship type	2014 Number	2014 DWT	2015 Number	2015 DWT	2016 Number	2016 DWT	2017 Number	2017 DWT
Bulk carrier	376	1,462,563	322	1,285,890	311	1,193,979	292	1,134,588
Container ship	43	764,596	50	962,469	51	1,041,769	64	2,692,977
LPG tanker	6	30,789	7	39,389	7	39,389	6	33,880
Chemical Tanker	72	548,223	62	446,465	59	473,089	55	448,992
Asphalt Tanker	2	22,738	3	42,666	3	42,666	3	42,666
Passenger ship	109	41,708	116	38,023	125	37,966	129	38,018
Ferry	49	14,047	50	12,296	53	12,050	52	11,768
Fishing boat	227	9,185	229	8,838	244	8,838	279	8,646
Tug	126	2,776	133	2.776	148	2.776	153	2.776
Fuel and Processed oil Tanker	87	870,957	94	886,761	94	888,409	93	1,187,184
Crude oil Tanker	2	300,544	2	300,544	2	300,544	4	615,450
Dry dock	44	287	49	8,287	53	13,125.87	57	13,125.87
Work boat	99	65,782	99	52,743	106	54,661	117	65,087
Recreational boat	101	837	121	2,552	123	2,552	121	2,552

Table 2. Ship types and their average ages of the merchant ship fleet of Turkey in 2015 (GISBIR 2018).

Ship type	Average age
General cargo	26.4
Bulk carrier	11.1
Passenger boats	21.1
Chemical tanker	8.8
Tugs and work boats	22.7
Product tanker	19.8
Fishing vessels	19.9
Container ship	13.1
Ro-Ro	27.1
Crude oil tanker	6.9
Supply vessels	27.0
LPG tanker	21.7
Others	25.0

levels revealed that most of the samples from the Aliağa were polluted with Hg, Cd, Pb, Cu, Zn, Mn and Ni. The main sources of these emissions are from the low alloyed steel materials.

3.2. Life cycle impact assessment

In this stage, it is aimed to identify and quantify environmental impacts of emissions arising from the inventory or resources consumed and caused by all inputs from, and outputs to, the environment calculated in the life cycle inventory phase and at aggregating them to a set of impact categories and specific indicators. In the analysis, the data evaluated with The CML-IA method (impact assessment method of the Center of Environmental Science of Leiden University) (Guinée et al. 2002) were used for the classification and characterisation stages. CML can be expressed as

Table 3. Sources and category of data collected and used in this study.

Processes	Phase	Data category	Sources of information / name of process[a]
Steel forming and joining	Shipbuilding	Selected generic data (amount of loss during shipbuilding process has been collected from the shipyards)	Ecoinvent 3.0 database low alloyed steel
Steel forming and joining	Shipbuilding	Selected generic data	Ecoinvent 3.0 database CO_2
Steel forming and joining	Shipbuilding	Selected generic data	Ecoinvent 3.0 database O_2
Steel forming and joining	Shipbuilding	Selected generic data	Ecoinvent 3.0 database LPG
Steel forming and joining	Shipbuilding	Selected generic data	Ecoinvent 3.0 database electricity, high voltage, at grid/kWh/TR
Steel cutting	Ship recycling	Selected generic data	Ecoinvent 3.0 database scrap steel (waste management) for the market
Steel cutting	Ship recycling	Selected generic data	Ecoinvent 3.0 database Diesel oil for the market
Transportation	Ship recycling	Selected generic data	Ecoinvent 3.0 database Transport, truck 21 t, Euro 5/ tonnes km/RER

[a]Dataset name of products, process and services selected in the ecoinvent database.

> an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity). CML has characterisation factors for more than 1700 different flows. The characterisation factors are updated when new knowledge on substance level is available. (Giama et al. 2018)

The potential impact categories assessed were abiotic depletion (AD; kilograms of antimony equivalent [kg Sb eq]), acidification (AC; kg sulphur dioxide [SO2] eq), eutrophication (EP; kg phosphate [$PO4^{3-}$] eq), global warming (GW; kg carbon dioxide [CO2] eq), ozone layer depletion (ODP; kg trichlorofluoromethane [CFC-11] eq), human toxicity (HT; kg 1,4 dichlorobenzene [1,4-DB] eq), freshwater ecotoxicity (FE; kg1,4-DB eq), marine ecotoxicity (ME; kg 1,4-DB eq), terrestrial ecotoxicity (TE; kg 1,4-DB eq) and photochemical oxidant formation (PO; kg 1,4-DB eq).

The results as the shares of phases have been summarised in Figure 2.

The global warming impact potential (over 100 years) is dominated by emissions of fossil fuel-derived carbon dioxide for all the phases, converting emissions of various greenhouse gases (GHG) into a global warming score established by the

Table 4. Inventory of selected emissions of a tug boat as an example.

Heavy metal	Emission to	Sources	Shipbuilding phase	Ship recycling phase
Fe	Air (kg)	Steel, O_2, scrap steel	2.79	0.474
	Water (tn lg)	Steel, scrap steel	1.74	37.7
	Soil (kg)	Steel, scrap steel	13.6	2.64
Cr	Air (kg)	Steel	22.9	0.0257
	Water (tn lg)	Electricity, O_2, steel, scrap steel	35.1	62.1
	Soil (kg)	Electricity, LPG, O_2, steel, scrap steel	6.24	1.35
	Air (kg)	Steel, scrap steel	443	18.9
Mn	Water (tn lg)	Electricity, steel, scrap steel	489	442
	Soil (kg)	O_2, steel, scrap steel	421	82.6
	Air (kg)	Steel	5.82	0.0633
Zn	Water (tn lg)	Steel, scrap steel	180	39.9
	Soil (kg)	Steel, scrap steel	237	62.5
	Air (kg)	CO_2, steel, scrap steel	42	4.96
Cd	Water (tn lg)	Steel, scrap steel	3.04	0.583
	Soil (kg)	Steel, scrap steel, O_2	409	97.2
	Air (kg)	Steel, scrap steel	861	50.1
Ni	Water (tn.lg)	Steel, scrap steel	121	190
	Soil (kg)	O_2, steel, scrap steel	2.28	0.582
	Air (kg)	Steel, scrap steel	2.05	0.045
Pb	Water (tn lg)	Steel, scrap steel	4.21	68.7
	Soil (kg)	Steel, scrap steel	4.92	1.33
	Air (kg)	Steel	306	0.984
	Water (tn lg)	Electricity, O_2, steel, scrap steel	63.9	3.11
Hg	Soil (kg)	Diesel fuel, electricity, LPG, transportation, O_2	2.99	1.51
Cu	Air (kg)	Steel, scrap steel	1.4	0.0732
	Water (tn lg)	Steel, scrap steel	0.0399	2.41
	Soil (kg)	Steel, scrap steel, CO_2, O_2	18.7	2.46

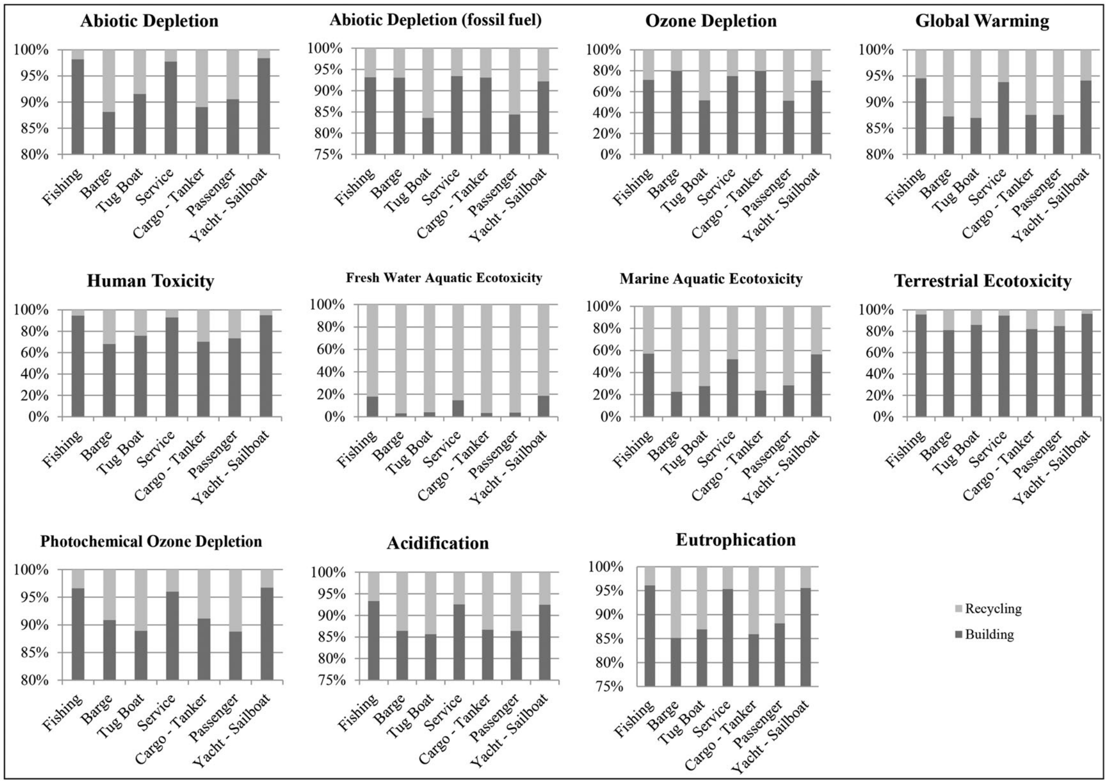

Figure 2. Environmental impact categories of shipbuilding and ship recycling phases for different type of ships.

Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007). GHG emissions have been converted into CO2 equivalent (eq) emissions using the latest GWP coefficient based on a 100-year time horizon in order to give one single indicator that gives the overall climate change impact of the system under studied (Zuin et al. 2009).

The air acidification impact potential is dominated by emissions of sulphur oxides and nitrogen oxides, which together comprise over 98% of potentially acidifying emissions for all the phases. The impact on ozone depletion is mainly due to the emissions of halon 1301 which will be phased out in near future. The eutrophication of water impact potential arises primarily from the release of phosphates and chemical oxygen demand due to the release of organic materials for the phases.

The highest impacts of ship types can be seen in Table 5. According to this brief information, ship types, whose more complicated forms such as fishing boat and recreational boat, pose higher impact than ship types whose simplified forms such as barge, tug boat and tankers.

Table 5. The ship types whose highest (H) and lowest (L) impact categories in the dominant phase.

Impact categories	Shipbuilding	Ship recycling
Abiotic depletion	H: Recreational vessel L: Barge	
Abiotic depletion (fossil fuel)	H: Fishing boat, barge, tanker, cargo L: Tug, passenger vessel	
Ozon depletion	H: Barge, cargo, tanker L: Passenger vessel	
Global warming	H: Fishing boat L: Barge, tug, passenger vessel	
Human toxicity	H: Passenger vessel L: Recreational vessel	
Fresh water aquatic ecotoxicity		H: Barge L: Recreational vessel
Marine aquatic ecotoxicity		H: Barge L: Recreational vessel
Terrestrial ecotoxicity	H: Recreational vessel L: Barge, tanker, cargo	
Photochemical ozone depletion	H: Recreational vessel L: Passenger vessel	
Acidification	H: Fishing boat, recreational vessel L: Barge	
Eutrophication	H: Fishing boat L: Barge, tug boat	

4. Conclusions

As the environmental impacts per value created are higher than those at the operating phase, the impacts of ship in different types during two significant phases, shipbuilding and ship recycling, have been determined by life cycle assessment approach in this study. Data collected from the related sites of Turkey have been used. From the results obtained from this model, it would be concluded as follows:

(1) Shipbuilding phase is prominent by 85% of the total impact in almost all categories except ozon depletion and marine aquatic ecotoxicity.

(2) The boats' more complicated forms (fishing boats, yachts and sailboats) have more impact than the ships' more simplified forms such as barge, tanker, bulk carrier, passenger and service boats. From these, negative environmental impacts of ships would be decreased from the early design stage. Designing a ship to dismantle easily in terms of energy (including labourship) and materials results in eco-friendly shipbuilding and ship recycling.
(3) At the first half of 2018, energy mix of Turkey is reported by the Ministry of Energy and Natural Resources (MENR 2018). Based on this report, 28.5% of electricity production was obtained from natural gas, 36.4% from coal, 22.4% from hydropower, 6.3% from wind, 2.3% from geothermal, 2.4% from solar energy and 1.6% from other sources. Decreasing the share of coal in the current energy mix of Turkey will cause a decrease in negative environmental impacts of the marine industry as a whole.
(4) Because in the shipbuilding phase purchasing of steel as raw materials and its production from ore and its process have been included, the impacts of the shipbuilding phase have been higher than those of the ship recycling phase. The construction material, itself, causes and determines main environmental impact share in the marine industry.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Gökdeniz Neşer http://orcid.org/0000-0001-9218-0181

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