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# Bionics and green technology in maritime shipping: an assessment of the effect of Salvinia air-layer hull coatings for drag and fuel reduction

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To save energy and reduce environmental impacts, new technologies towards a development of a sustainable 'greener' economy are needed. The main opportunity to improve sustainability by reducing emissions is within the transport sector. More than 90% of all goods worldwide are transported by ships. Particularly maritime ships using heavy fuel oil and marine gas oil play a major role. The total fuel consumption of shipping in 2016 was about 250 m t (domestic ca. 50 m t, international shipping ca. 200 m t). The vast portion of the energy consumption of a ship is the need to overcome the drag between ship hull and water—depending on the shape of the vessel and its size up to 90% of total fuel consumption. This means reducing drag helps to save fuel and reduces carbon emissions as well as pollution considerably. Different techniques for drag reduction are known, e.g. the micro-bubble technique or the bulbous bow. We investigated a novel bioinspired technique since 2002: the application of biomimetic surfaces with long-term stable air layers on ship hulls, serving as a slip agent. This technology is based on the Salvinia Effect, allowing a permanent stabilization of air layers under water. In this case study, we analysed the possible savings, which also could be combined with modified micro-bubble technologies. We calculated, based on a selection of five ship types, representing 75% of the world fleet, that air-layer hull coatings could lead to estimated savings of 32.5 million tons of fuel (meaning 13.0% of the worldwide shipping fuel consumption), equal to 18.5 billion US$ and 130.0 million tons of $CO_{2e}$ per year. The positive impacts on global temperature and other greenhouse gases are calculated and could be a contributing factor in accomplishing the UN Sustainable Development Goals and the Paris Agreement to the UN Framework Convention on Climate Change. The study is a contribution to enhance our patchy knowledge concerning the potential economic and ecological benefit of bionics and biomimetic technologies.

This article is part of the theme issue 'Bioinspired materials and surfaces for green science and technology'.

## 1. Introduction

Since the beginning of the industrial revolution, the production of goods and the need for energy have continually risen: an effect of the growth of Earth's population and globalization. Faster and efficient ways to transport goods were required. At the beginning of the Anthropocene, we have to rethink our well-established paradigms for the future [1,2]. The current levels of economic activities and standard of living require energy, usually still based on fossil fuels. Increasing emissions are supposed to be the main driver for global warming. New paradigms or a 'social transformation towards a more sustainable economic system' [1,3] with an integration of social, cultural, ecological and economic aspects are necessary [2,4]. First approaches towards a 'greener economy' have been introduced, e.g. the globally increasing numbers of wind turbines and solar panels.

A promising approach is bioinspired 'learning from nature', bionics or biomimetics [5]. Bionic technologies could be an important component contributing to the 17 UN Sustainable Development Goals (SDGs) of the Agenda 2030 [6].

Drag of moving solids in a liquid (e.g. ships in water) can be reduced by different physical mechanisms. We have shown that a persistent air layer between ship hull and water is most effective in reducing friction and drag (surveys in [7–9]). In this paper, we focus on an economic and ecological assessment of the effect of persistent air layers under water (Salvinia Effect [7,10]) for drag reduction and consequently fuel saving. Although bionics and biomimetics play an important role in research, economy and public awareness, very few data are available concerning the actual economic potential and ecological benefit in this field. The assessment and figures presented here fill a gap in this requirement.

## 2. Biomimetic technologies: economic and ecological value

Bioinspiration is as old as mankind (historical survey in [5]). It is estimated [11] that by 2030 biomimetic technologies may account for 425 billion US$ of the Gross Domestic Product (GDP, in terms of 2013 dollars) in the USA alone; an additional $65 billion could possibly be saved through reduced resource depletion, emissions and pollution. This could mean on a global scale $1.6 trillion of total output or GDP with another $500 million added by resource savings, emission and pollution mitigation (by 2030) [11].

The main sectors with resource saving opportunities are transportation, energy and manufacturing [12]. Considering the increasing global transport activities resulting in increasing emissions, environmental protection is a crucial factor in logistics. Ships transport more than

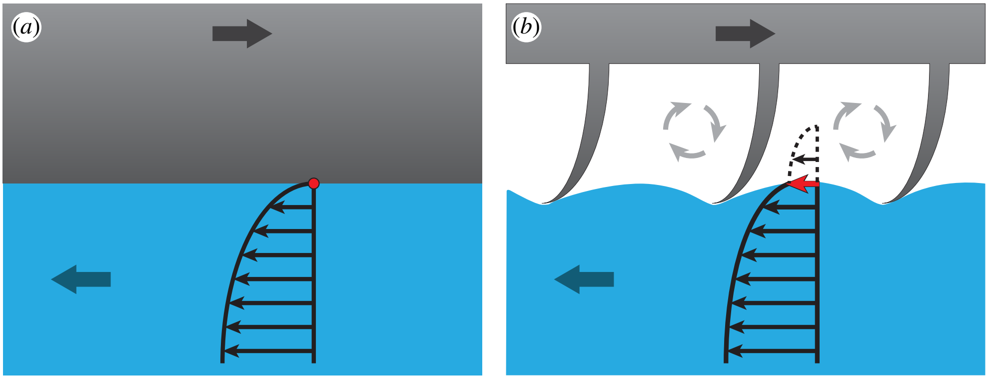

**Figure 1.** Schematic of the drag reduction by air layers. (*a*) Flow profile on a conventional ship hull. The water velocity at the surface boundary layer is zero. (*b*) An air layer functions as slip agent, the water velocity at the interface is larger than zero, drag is reduced. Adapted from [8].

90% of all goods worldwide [13,14]. Owing to the major role in global trade and the high share in emissions of around 2.6% of globally emitted $CO_{2e}$ in 2012 [15] the shipping industry and especially the maritime ships, with their use of heavy fuel oil and marine gas oil, are a major contributor to the transport sector's emissions.

In 2015, 10 billion tons of goods were transported by ships [16]. The shipping industry is one of the major fuel consumers. In 2016, the total fuel consumption of all transport ships (ca. 71% of total shipping consumption) and cruise ships (ca. 4% of total shipping consumption) worldwide was about 187.5 m tons [15,17]. By far the largest portion is needed to overcome the drag with the surrounding water—depending on the ship type up to 90% [18].

Techniques to reduce this drag lead to a considerable reduction of fuel consumption, emission, and pollution and to a reduction of costs. Different technologies to realize drag reduction have been developed. For example, the ejection of micro-bubbles in order to achieve air lubrication—a technique that is possibly biomimetic and occurs on penguins [19]. Other examples are the bulbous bow [20,21], or riblet surface structures inspired by shark skin [22]—the latter successfully applied by the 3M saw tooth riblet coating for boats, e.g. in the America's cup [23] and on Speedo-Swimsuit; however, it is questionable which role the swimmer locomotion and even possibly trapped air layers play [22,24].

## 3. Air layers for drag reduction in water

A different approach is the use of persistent air layers on the ship hull. In 1995, Latorre *et al.* [25] showed that the drag of water streaming over a thin layer of air might be reduced up to about 80% compared to a smooth surface because of the lower (55 times) viscosity of air. The basic principle of this drag reduction is shown in figure 1. If water flows over a smooth solid surface, the velocity at the boundary layer is zero due to the friction between water and surfaces. If an air layer is switched between the solid surface and the liquid, the velocity is higher than zero—the lower viscosity reduces the transmission of friction forces.

Already in 2007, we performed measurements with a prototypic hydrophobic textile at the German 'Development Centre for Ship Technology and Transport Systems (DST)' (figure 2*a*). A drag reduction of up to 10% [26,27] was measured. In following experiments at the Institute of Fluid Mechanics at the University of Rostock, a reduction of the friction of more than 30% on a flow profile covered with a more elaborate air retaining flock surface was achieved [28]. These impressive results indicate the potential of air retaining surfaces.

Persistent air layers under water evolved in many aquatic and semiaquatic organisms as an evolutionary adaptation to drag reduction or respiration under water. Optimized examples are the floating fern *Salvinia* (figure 3*a*,*c*) [10] with a most sophisticated 'technology' using hydrophilic

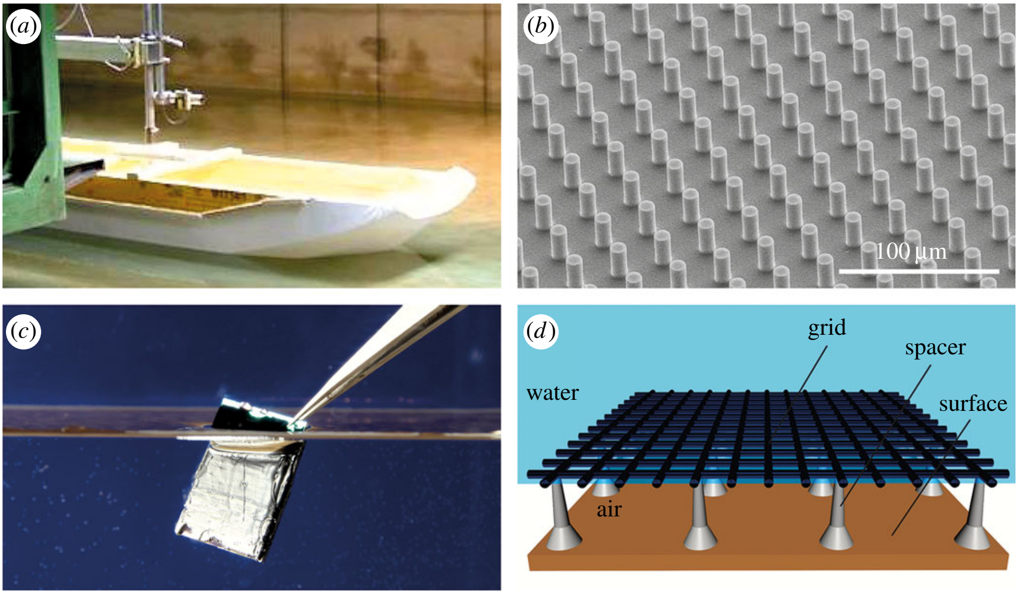

**Figure 2.** Technical prototypes of air retaining surfaces. (*a*) First measurement with a 7 m boat with a hydrophobic air retaining hull at the German Development Centre for Ship Technology and Transport Systems (DST) resulted in a drag reduction about 10%. (*b*) SEM image of the micropillars on a prototypical bionic surface. (*c*) Submerged sample of surface covered with hydrophobic carbon nanotubes (CNT), retaining an air layer under water. (*d*) Schematic of the Air Retaining Grids (AirGrids).

chemical heterogeneities on a superhydrophobic surface [29], or the backswimmer *Notonecta* (figure 3*b*,*d*) [31]. Reviews and surveys are given in [7–9].

Four criteria are important for long-term air retention under water [8]: (1) hair-like structures, (2) a hydrophobic chemistry, (3) undercuts and (4) the elasticity of the structures. Additionally, hydrophilic pins (Salvinia Paradox) may occur. Examples of technical prototypes are shown in figure 2.

For an easier and more cost-effective production of air retaining surfaces, we developed ‘Air Retaining Grids’ (AirGrids) [7,8]. In this case, the air layer is retained by hydrophobic grid-like structures mounted at a defined distance on the ship hull surface. This technique allows a combination with the well-established micro-bubbles technique. The micro-bubbles can be used to refill the air layer in case of a loss of air. But as the air is retained by the AirGrid surface, only a reduced quantity of supply is necessary, and the additional energy needed for the bubble producing pumps is reduced.

## 4. Case study: calculated fuel-, emission-, and cost-savings, based on five maritime ship types

To investigate market, climate and environmental potential of the air retaining hulls, we calculated the possible savings of fuel, emissions, air pollution and costs for five different types of maritime ships and for different drag reduction values. An additional possible benefit from the antifouling effect of air layers is discussed in the conclusions.

We discuss three scenarios (compared to the status quo) of possible drag reduction related to the Salvinia Coating on fuel (measured in tons and US$) and emissions (measured in $CO_2$ equivalents, $CO_{2e}$).

The five types of maritime ships selected represent the three fleet categories with the highest share in the world fleet (in terms of dwt): bulk carriers, oil tankers and container ships; additionally a cruise ship (*Queen Mary II*) and Ultra Large Container Vessel (ULCV) (*Emma Maersk*) were compared. With 43.1% bulk carriers, 27.9% oil tankers and 13.5% container ships

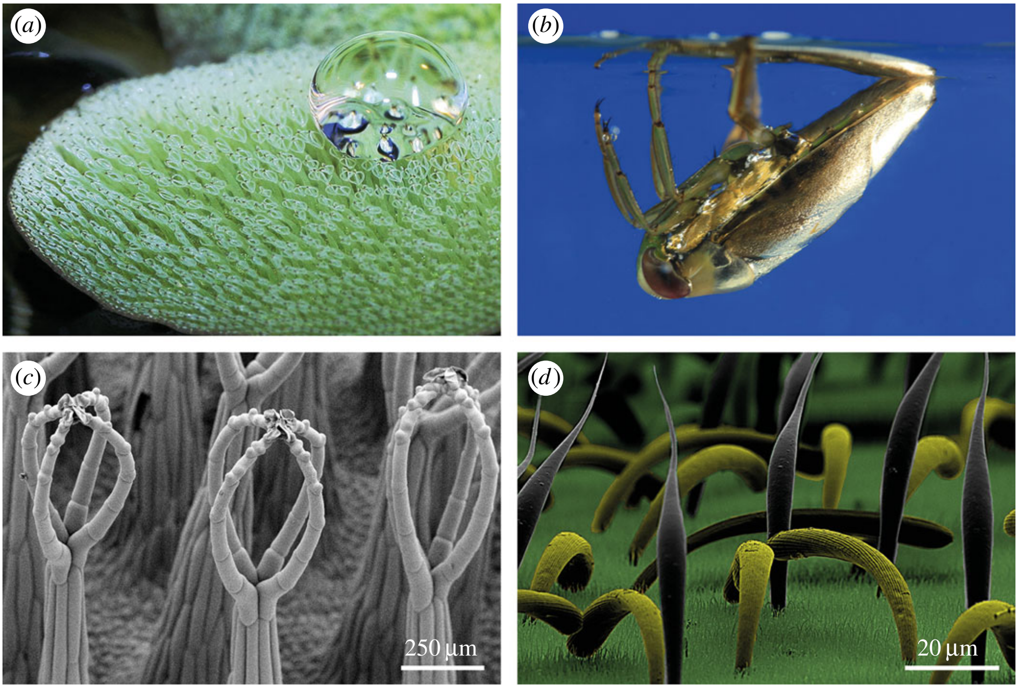

**Figure 3.** Biological prototypes with persistent air layers. (*a*) Leaf of the floating fern *Salvinia molesta*. (*b*) Backswimmer *Notonecta*. (*c*) SEM of the hierarchically structured, eggbeater like shaped trichomes on the surface of *Salvinia* responsible for the air retention. (*d*) Hierarchical structure on the surface of *Notonecta*. Long hairs (setae) and a dense floor of 'microtrichia' stabilize the air layer. Sources: (*a*) [29]; (*b*) [30].

in the world fleet [16], the selected types can serve as a representative sample for the current world fleet.

*Ikuna*, *Prem Divya* and the five identical container ships have been chosen because of the availability of fuel consumption data from actual observations and their ship type's share in the world fleet. The ULCV *Emma Maersk* and the cruise ship *Queen Mary II* have been chosen due to their representation of the trend towards an increasing ship size, especially in the area of the container and cruise ships. Cruise ships (and ferries) have only a global share of 0.3%, but cruise ships in particular offer the possibility for consumers to influence the carbon footprint.

Values for the fuel consumption are based on the optimal values given by the engine manufacturers, because no other empiric sources are available. Realistically they could be higher (compare automobile manufacturer data). All calculations in the following chapters are based on the subsequent data and assumptions:

The emission factors per ton of fuel consumed are described in table 1. Apart from the black carbon factor, which varies in the literature and is therefore indicated as a mean value [32–36], all numbers are taken from the International Maritime Organization's Second IMO GHG Study 2009 [37].

Main engine fuel costs represent the largest single item and account for about 50% of the total cost of a ship's operational expenses [38,39]. These costs have their origin mostly in the frictional resistance between the ship hull and the surrounding water—up to 90% of the ship's total resistance [40,41]. For our calculations, we assume a lower share of 65% of frictional resistance, to cut out the extreme cases.

So far a reduction of friction by an air retaining surface of 30% [28] has been achieved. In order to cover a broad band of possible broad scale solutions, we assume three different friction reduction scenarios of 5%, 10% and 20% for our calculations.

**Table 1.** Emission factors per ton of fuel consumed. All values except the black carbon factor are taken from [32–36]. The black carbon factor varies in literature and has a mean value of 0.15 kg per ton.

| emission | emission factor in kg per ton of fuel |
|---|---|
| CO | 7.4 |
| $CH_4$ | 0.3 |
| $CO_2$ | |
| residual fuel oil | 3130 |
| marine diesel oil | 3190 |
| $SO_2$ | |
| residual fuel oil | 54 |
| marine diesel oil | 10 |
| $NO_x$ | |
| slow-speed engines | 85 |
| medium-speed engines | 56 |
| $PM_{10}$ | |
| residual fuel oil | 6.7 |
| marine diesel oil | 1.1 |
| non-methane volatile organic compounds (NMVOC) | 2.4 |
| $N_2O$ | 0.08 |
| black carbon (BC) | 0.15 |

For the calculations, we assume a price of 570 US$ per ton of fuel. This price varies, but looking at the 10-year average (2007–2017), this is a reasonable assumption for a mixed fuel (High Sulfur Fuel Oil, Marine Gas Oil) calculation [42].

For each of the five ship types, the calculated values for the possible savings in kg per nautical mile, as well as the calculated possible cost, emission ($CO_2$ and other greenhouse gases like $CO_{2e}$) and pollution savings are shown. In each case, we calculated the values for the three friction reduction scenarios.

In order to put all these figures in a more comprehensive context, we calculated the values for a fictional journey for each of the ship types.

## (a) Bulk carrier *Ikuna*

The bulk carrier *Ikuna* (figure 4*a*) was built in 1986 and has a dead weight tonnage of 6666 tons. It is a ship of the Indian company Mercator Limited. It is powered by two medium-speed 4-stroke engines and the initial fuel consumption (shortly after cleaning) at a reference speed of 11 knots is around 47 kg per nautical mile [48]. It was decommissioned in 2011. Its total emission values as well as the calculated possible savings in the three scenarios are given in the electronic supplementary material, table S1. Our calculations showed possible fuel savings of 1.72–6.89 kg and cost savings of 0.98 US$ to 3.93 US$ per nautical mile in the three scenarios for the bulk carrier.

For the *Ikuna*, we calculated the values for a fictional journey in India from Vishakhapatnam Terminal to Calcutta Terminal of around 440 nautical miles (one way). The calculated possible fuel savings for this journey are between 757.9 and 3031.6 kg, meaning $CO_2$-emission savings between 2372.2 kg and 9488.9 kg and cost savings of 432.0 US$ to 1728.0 US$. The detailed results for the three scenarios are given in electronic supplementary material, table S2.

**Figure 4.** Images of the ships included in this study. (*a*) The bulk Carrier *Ikuna*, (*b*) Crude Oil Tanker comparable to *Prem Divya*, (*c*) a container ship representing the Five Container Ships of this class, (*d*) the Ultra Large Container Vessel *Emma Maersk* and (*e*) the Cruise Ship *Queen Mary II*. Sources: (*a*) with kind permission from Cody Williams [43]; (*b*) adapted [44]; (*c*) [45]; (*d*) adapted from [46]; (*e*) adapted from [47].

## (b) Crude Oil tanker *Prem Divya*

The Aframax-class crude oil tanker *Prem Divya* (comparable oil tanker figure 4*b*) was built in 1998 and has a dead weight tonnage of 109 227 tons. It is a ship of the Indian company Mercator Limited. It is powered by a slow-speed 2-stroke engine and the initial fuel consumption (shortly after cleaning) at a reference speed of 11 knots is around 140 kg per nautical mile [48]. It was decommissioned in 2012. Its total emission values as well as the calculated possible savings in the three scenarios are given in electronic supplementary material, table S1. Our calculations showed possible fuel savings of 5.07–20.28 kg and cost savings of 2.89 US$ to 11.56 US$ per nautical mile in the three scenarios for the oil tanker.

For the *Prem Divya*, we calculated the figures for a fictional journey from Bahrein to Calcutta of around 2700 nautical miles (one way). The calculated possible fuel savings for this journey are between 13 689.0 and 54 756.0 kg, meaning $CO_2$-emission savings between 42 846.6 and 171 356.3 kg and cost savings of 7802.7 US$ to 31 210.9 US$. The detailed results for the three scenarios are given in electronic supplementary material table S2.

## (c) Container ships

The five identical container ships belong to the Postpanamax-Class (figure 4*c*) and remained anonymous in the data source. They have a capacity of 8240 twenty-foot equivalent units and are powered by a slow-speed 2-stroke engine with an average speed of 20.5 knots and an average fuel consumption of 329 kg per nautical mile [48]. The total emission values as well as the calculated possible savings in the three scenarios for this ship class are given in electronic supplementary material, table S1 in the supplementary information. Our calculations showed possible fuel savings of 10.69 kg to 42.77 kg and cost savings of 6.09 US$ to 24.38 US$ per nautical mile in the three scenarios for this ship class.

For this ship class, we calculated the values for a fictional journey TA2—Eastbound (Baltimore, USA to Bremerhaven, Germany) of around 6800 nautical miles (one way) [49]. The calculated possible fuel savings for this journey are between 72 709.0 and 290 836.0 kg, meaning $CO_2$-emission savings between 227 579.2 and 910 316.7 kg and cost savings of 41 444.1 US$ to 165 776.5 US$. The detailed results for the three scenarios are given in electronic supplementary material, table S2.

## (d) Ultra large container vessel *Emma Maersk*

The ULCV *Emma Maersk* was built in 2006 as the first of eight identical container ships owned by the A.P. Møller-Maersk Group. She has a dead weight tonnage of 156 907 tons and can carry up to 15 000 twenty-foot equivalent units. She was holding the record for the world's largest ship and still holds the record for the world's largest and most powerful reciprocating engine: a slow-speed 2-stroke engine, the Waertsilae RT-flex96c [50,51]. On a slow-steaming load of 65%, the engine needs 520.2 kg fuel per nautical mile at a sailing speed of 16.38 knots [52]. The total emission values as well as the calculated possible savings in the three scenarios for this ship class are given in electronic supplementary material, table S1. Our calculations showed possible fuel savings of 16.91 kg to 67.63 kg and cost savings of 9.64 US$ to 38.55 US$ per nautical mile in the three scenarios for the ULCV *Emma Maersk*.

For the *Emma Maersk*, we calculated the values for a fictional journey AE10—Eastbound (Gdansk, Poland to Ningbo, China) of around 11 900 nautical miles (one way) [53]. The calculated possible fuel savings for this journey are between 201 187.4 kg and 804 749.4 kg, meaning $CO_2$-emission savings between 629 716.4 and 2,518,865.6 kg and cost savings of 114 676.8 US$ to 458 707.2 US$. The detailed results for the three scenarios are given in electronic supplementary material, table S2.

## (e) Cruise ship *Queen Mary II*

*Queen Mary II* with 151 400 gross tonnage and a length of 345 m is one of the largest operating cruise ships in the world. She entered service in 2004 and is powered by four Waertsilae 16V46 diesel engines running on heavy fuel oil and two General Electric LM2500+ gas turbines which run on marine gas oil. On full load, each engine and each turbine burns roughly 3 tons of heavy fuel oil and 6.5 tons, respectively, of marine gas oil per hour [54–56]. Given the approximate 345 days of operation according to the Cunard Lines cruise schedule [57] and an assumed all-time use of the diesel engines and a half-time use of the turbines, this results in a yearly fuel consumption of 99 360 tons of heavy fuel oil and 107 640 tons of marine gas oil. This totals 654 368.4 tons of $CO_2$ emissions per year—in average the same amount is emitted by roughly 354 779 German cars (130 g/km $CO_2$, yearly mileage of 14 200 km [58]). The total emission values as well as the calculated possible savings in the three scenarios for this ship class are given in electronic supplementary material, table S1. Our calculations showed possible fuel savings of 26.88–107.52 kg and cost savings of 15.32 US$ to 61.29 US$ per nautical mile in the three scenarios for the cruise ship *Queen Mary II*.

For *Queen Mary II*, we calculated the values for a journey from Dubai (United Arabic Emirates) to Southampton (United Kingdom) with a total distance of 6788 nm travelled [59,60]. The calculated possible fuel savings for this journey are between 110 506.8 and 442 027.1 kg, meaning $CO_2$-emission savings between 349 356.2 and 1 397 424.7 kg and cost savings of 62 988.9 US$ to 251 955.4 US$. The detailed results for the three scenarios are given in electronic supplementary material, table S2.

**Table 2.** Possible savings within the three scenarios selected.

| savings | scenario 1 (5%) | scenario 2 (10%) | scenario 3 (20%) |
|---|---|---|---|
| fuel (m t) | 8.13 | 16.25 | 32.50 |
| cost (billion US$) | 4.63 | 9.26 | 18.53 |
| $CO_{2e}$ (m t) | 32.5 | 65.0 | 130.0 |

## 5. Global perspective: benefit assessment of drag reducing air layer-coated ship hulls

Based on all non-military ships larger than 100 gross tonnage (in 2007) and the assumption that slow-speed diesel (SSD) engines are by far the dominating engine type [61] the following figures show the current situation in the global shipping industry.

Assuming a current global fuel consumption of approximately 250 million tons per year at a current price of 570 US$/t, this accounts for 142 billion US$ and represents roughly 1 billion tons of $CO_{2e}$ emissions.

Given a constant speed of the ships, the friction reduction due to the application of a Salvinia Coating could be up to 20% and would lead to estimated savings of 32.5 million tons of fuel, 18.5 billion US$ and 130.0 million tons of $CO_{2e}$. Since every ton of $CO_2$ emitted causes a mean increase in global temperature of $1.5 \times 10^{-12}$ C° [62,63] the total avoided increase per year assumed would be approximately 0.0002°C. Savings from Salvinia Coatings are thus equivalent to 14.30% of Germany's emissions [64] and equal to a reduction of about 0.36% of the current global $CO_2$ emissions [65].

This nearly outperforms the efficacy of the Australian carbon tax's estimated 160 million tons reduction (in 2020) [66]. More than one third of the cumulated savings of 324 million tons of $CO_2$ emissions in 2030 of the EU regulation limiting car's $CO_2$ emissions to $95\,\mathrm{g\,km^{-1}}$ [67] is roughly met by a Salvinia Coating. It would almost reach the estimated savings of all other measures introduced by the IMO by 2020 (151.5 million tons) [68].

## 6. Conclusion

The study is a contribution to enlarge our insufficient and patchy knowledge concerning the potential economic and ecological benefit of bionic and biomimetic technologies.

Maritime shipping is one of the main consumers of fossil fuels and thus a strong emitter of greenhouse gases. The International Maritime Organization (IMO) has already acted towards a sustainable so-called 'blue economy' on the sea and introduced more restrictions in 2013: In 2020, new ships must improve their efficiency by 10%, in 2025 by 20% and in 2030 by 30%, aiming at 50% emissions reduction by 2050 [13].

The main part of the fuel consumption of ships is the need to overcome the drag between ship hull and water. In this study, we calculated the possible fuel, cost and emission savings by biomimetic, drag reducing ship coatings based on long-term stable air layers between ship hull and water. We could show that a drag reduction of 20% by such Salvinia Effect Coatings could lead to savings of 32.5 million tons of fuel, equal to 18.5 billion US$ and 130.0 million tons of $CO_{2e}$ per year (table 2).

In addition to the drag reducing properties of air retaining surfaces, one can expect also an antifouling effect from such coatings [69]. If we include an additional drag reduction of 25% due to antifouling effects to our calculations, this would mean additional savings of 40.6 million tons of fuel, 23.2 billion US$ and 162.5 million tons of $CO_{2e}$.

Our results show the high potential of biomimetic air retaining surfaces. Providing a drag reduction of 20% and additional antifouling properties, these coatings could lead to a saving of almost 1% of the worldwide $CO_2$ emissions.

However, one should be aware that the production of solid waste (e.g. plastics) is another of the serious problems affecting the environmental impact of shipping. From the view of biologists, the almost global migration of invasive species (like *Cercopagis*, *Eriocheir, Carcinus* or even diseases like Cholera)—mostly associated with ballast water discharge—may be an irreversible result with a negative long-term impact [70,71].

However, at the same time 'biological prototypes' offer often sustainable technical biomimetic solutions. Friction and thus fuel and emission reduction (the major global goal in our changing environment) based on air retaining surfaces of *Salvinia* and other organisms provide solutions for environmentally friendly green technologies.

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