Tackling marine plastic debris

The possibilities of marine plastic debris recycling

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Abstract

This work concentrates on marine plastic debris and its collection and recycling methods as one possible answer to the rising amount of plastic in marine environments. There are six reasons for debris collection and recycling: aesthetics, habitat and wildlife protection, human health, fishing efficiency, ease of implementation and environmental awareness raising. When analysing different recycling methods, it is revealed that mechanical recycling cannot be applied to marine plastic debris. Feedstock recycling, where plastics are converted into raw materials again that can be used to make new plastic products, is possible but would be economically inefficient. Furthermore, it cannot be used for reducing collection costs, as opposed to energy recovery, for instance. By using energy recovery, for example by gasification of marine plastic debris, fuel can be produced. This fuel can then be used for the collecting ship. Furthermore, volumes of the collected material can be reduced. Therefore, basic calculations are made for the masses of plastic debris collected on the water surface and the energy recovered through recycling of marine plastic debris. The calculated scenario comprises on-board gasification in a fluidized bed reactor and three different plastic concentrations on the water surface. First results for the mass flow and product yield as well as for fuel savings are given, if the gasification product is used as fuel for the collection ship. The highest relative fuel savings (14%) where calculated at 0.6 m/s collection speed with maximum plastic concentrations. Considering the optimal velocity of 0.6 m/s regarding both, the emissions and the relative power savings, the vessel's engine has to be optimized at 2.4 kW. The highest amount of plastic is expected to be collected at 2 m/s, namely 1 323 kg of marine plastic per year.

Diese Arbeit beschäftigt sich mit dem Einsammeln und Recycling von Plastikabfall im Meer als eine der möglichen Antworten auf die zunehmende Ansammlung von Kunststoff in marinen Ökosystemen. Das Einsammeln und Recyclen von marinem Kunststoff erfolgt aus sechs Gründen: Ästhetik, Schutz von Lebensräumen und Tieren, Schutz der Gesundheit von Menschen, Effektivität der Fischerei, einfacher politischer Umsetzbarkeit und Bewusstseinsbildung. Die Recherche zu verschiedenen Recyclingmethoden von marinen Kunststoffen hat ergeben, dass werkstoffliches Recycling von marinem Kunststoff nicht umsetzbar ist. Rohstoffliches Recycling, bei dem aus dem Kunststoff wieder Rohmaterial für neue Kunststofferzeugnisse gewonnen werden kann, ist zwar möglich, ökonomisch allerdings nicht effizient. Außerdem kann es nicht zur Reduktion von Treibstoffkosten genutzt werden, anders als bei der Energierückgewinnung beispielsweise durch Vergasung. Zudem reduziert Energierückgewinnung das Volumen des gesammelten Kunststoffs. Es wurden Erträge einer Einsammlung von Kunststoff an der Wasseroberfläche mit einem Netz bei drei verschiedenen Kunststoffkonzentrationen im Meer mit anschließender Vergasung berechnet. Die höchsten relativen Treibstoffeinsparungen, bei denen 14% des Schiffsdiesels durch Gas aus dem Recyclingprozess ersetz werden kann, wurden bei einer Geschwindigkeit des Schiffes beim

Einsammeln von 0.6 m/s und maximaler Kunststoffkonzentration im Meer errechnet. Bei dieser, sowohl in Bezug auf die relative Leistungsersparnis, als auch auf Emissionen, optimalen Geschwindigkeit, ist der Schiffsmotor auf eine Leistung von 2.4 kW zu optimieren. Die höchste Masse an gesammeltem Kunststoff ist bei einer Geschwindigkeit von 2 m/s mit 1 323 kg jährlich zu erwarten.

1 Symbols and abbreviations

abbreviation	unit	definition	reference
BPA		bisphenol A	
EPR		extended Producer Responsibility	
EU		European Union	
GCV		gross calorific value	
IMO		International Maritime Organisation	
MARPOL		Marine pollution; in the context of the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978	
MPPRCA		Marine Plastic Pollution Research and Control Act	
MPW		Mixed plastic waste	
OSPAR		OSPAR Commission; Named after the original Oslo and Paris Conventions	(OSPAR Commission, n.d.)
PBDE		polybrominated diphenyl ether	
POP		persistent organic pollutant	
PUR		polyurethan	
PVC		polyvinyl chloride	
UNEP		United Nations Environment Programme	
UNCLOS		United Nations Convention on the Law of the Sea	
Cap_{net}	m^2/h	"Nets efficiency (without frame) of cleaning water area from litter", area covered with the net; $Cap_{net} = 3600*k_{sh}*L*v$	(Smailys et al., 2016)
k_{sh}	-	coverage coefficient: *0.7*	(Smailys et al., 2016)
L	*m*	length of net	(Smailys et al., 2016)
g_f^{net}	kg/m^2	fuel consumption and air pollutant emissions when trawling the net with ship used in the trials	(Smailys et al., 2016)
eCO_2	g/kg_{fuel}	measured CO_2 emissions ("specific air pollutans emission factors")	(Smailys et al., 2016)
eSO_2	g/kg_{fuel}	measured SO_2 emissions ("specific air pollutans emission factors")	(Smailys et al., 2016)
eNO_x	g/kg_{fuel}	measured NO_x emissions ("specific air pollutans emission factors”)	(Smailys et al., 2016)
eCO	g/kg_{fuel}	measured CO emissions ("specific air pollutans emission factors”)	(Smailys et al., 2016)
e_{CO}^{net}	kg/m^2	“$e_{netj} = E_{netj}/Cap_{net}$; “ “j= air pollutant ($CO_2$, CO, NOx etc.)”	(Smailys et al., 2016)

		CO Emissions per m^2 of the area covered with the net	
e_{NOx}^{net}	kg/m^2	“$e_{netj} = E_{netj}/Cap_{net}$; “ “j= air pollutant ($CO_2$, CO, NOx etc.)” NO_x Emissions per m^2 of the area covered with the net	(Smailys et al., 2016)
e_{SO2}^{net}	kg/m^2	“$e_{netj} = E_{netj}/Cap_{net}$; “ “j= air pollutant ($CO_2$, CO, NOx etc.)” SO_2 Emissions per m^2 of the area covered with the net	(Smailys et al., 2016)
e_{CO2}^{net}	kg/m^2	“$e_{netj} = E_{netj}/Cap_{net}$; “ “j = air pollutant ($CO_2$, CO, NOx etc.)” CO_2 Emissions per m^2 of the area covered with the net	(Smailys et al., 2016)
$e_{CO2}^{net,y}$	$kg_{CO2}/year$	yearly CO_2-emissions	
$e_{CO}^{net,y}$	$kg_{CO}/year$	yearly CO-emissions; $e_{CO}^{net,y}=e_{CO}^{net}*Cap_{net}*365*24$	
$e_{NOx}^{net,y}$	$kg_{NOx}/year$	yearly NO_x-emissions	
$e_{SO2}^{net,y}$	$kg_{SO2}/year$	yearly SO_2-emissions	
fc	$kg_{fuel}/year$	yearly fuel consumption of the ship without savings	
LCV_{Diesel}	MJ/kg	lower calorific value of marine diesel	
$LCV_{plasticgas}$	kJ/kg	lower calorific value of marine plastic debris	
P_{diesel}	*watt*	power needed for marine plastic debris collection	
$P_{plastic}$	*watt*	power received from plastic gasification available for use, power of plastic-gasification product	
$\mathbf{P_{diesel_{new}}}$	*watt*	power difference if marine diesel is replaced by the plastic-gasification product	
$\mathbf{P_{plastic_{rel}}}$	%	$P_{plastic_{rel}}$ is the relative amount of the quantity of marine diesel used by the engine that can be substituted by plastic gas produced on board from the collected plastic.	
v	m/s	speed of the ship	
y	$kg_{plastic}$	yearly plastic yield	
p	g/km^2	density or concentration of marine plastic in the trawling area	
r	$\frac{kg_{producer\ gas}}{kg_{plastic}}$	gas production rate	(Arena and Di Gregorio, 2014)

2 Introduction

The word “cheap” probably describes the duality of the image of plastics in modern society the best. It references a low price as well as low quality. In fact, plastics are so diverse, flexible and practical that we may find them in nearly every product. In recent years, a new connotation of plastics has emerged: scientists warn of the health risks of additives (Halden, 2010). This could change consumption behaviour, such as using plastic bags for hot edible items (Jayaraman et al., 2011). Nevertheless, the world production has, according to PlasticsEurope, risen from 225 in 2004 to 311 million tonnes plastics in 2014 (PlasticsEurope - Association of Plastics Manufacturers, 2015).

The inconvenient truth behind this consumption pattern is an enormous amount of plastic waste. 25.8 million tonnes of post-consumer plastics were produced only in 2014 (PlasticsEurope - Association of Plastics Manufacturers, 2015, p. 17). Each nation has its own methods of waste management but the debris that is leached into the oceans does not belong to a certain national territory. Litter is collected only in marine national territories, for example, on beaches. Once plastic debris enters the ocean, there is no collection or treatment. Oliver Stengel (Stengel, 2011, p. 75f) describes the outdated concept of nature from Francis Bacon (1620) which considers nature as an inexhaustible and indestructible source of what we need. This attitude explains why the leakage of plastic in the vast and deep sea has not been considered a problem for the public until the discovery of the “garbage patch” (Mitchell, 2015, p. 83) (see chapter 4.1). However, the concept of nature has changed and today, knowledge of the vulnerability of ecosystems is expanding and the awareness of the omnipresence of plastic in our lives and the environment is rising. Media („Im Plastik gefangen“ (Kirbach, 2015)), environmental organisations („Tüten töten Tiere“ (Albrecht, n.d.)) and others („Plastikabfall vergiftet die Meere und Tötet Meerestiere“ (Deutsche Stiftung Meeresschutz, n.d.)) have been drawing attention to the fact that plastic debris is finding its way into the environment, especially the marine environment. Plastic debris littering the world is considered problematic because it can be rated by the general public as ‘bad’ for animals and allegedly probably also for humans, aside from the fact that it ‘does not look nice’. Therefore, a policy should approach the problem of increasing quantities of marine plastic. Considering these previously mentioned partly excessively simplified arguments (for a more precise scientific problem description see chapter 4.2), a policy may conclude that plastic needs to be removed from the marine environment.

The following chapters will concentrate on marine plastic debris and its collection, as well as recycling methods as one possible answer to the rising amount of plastic in marine environments.

3 Aim and scope

The focus of this work is researching the possibilities of a plastic debris collection with a mobile offshore waste collecting and recycling facility, also referred to as collection ship. The idea is that plastic is collected in areas with high concentrations of plastic debris and that, this waste is recycled on board to produce fuel for the collecting facility in order to reduce the fuel cost of debris collection. A recycling on board is focused, because it is assumed that a transport of the collected plastic to the respective closest on-shore recycling facility produces more emissions and is more expensive than recycling on board. Furthermore, there are fluctuations of the plastic concentration (Liubartseva et al., 2016). Because of these fluctuations and the large area the accumulation zones of plastic cover (see also chapter 4.1), calculations in this work focus on collection with a ship, not a fixed barrier like the concept the Ocean Cleanup suggests. For a critical review of this fundamentally different approach to marine plastic collection see Martini (2014).

The description of the problem (chapter 4) gives an overview on the complexity of the topic of marine plastic debris and on current solutions for this problem. In particular, this chapter will give an overview on marine plastic debris and where it can be found (4.1) and will cover six reasons to collect and recycle marine plastic debris: Aesthetics (4.2.1), Fishing efficiency (4.2.4), Habitat and wildlife protection (4.2.2), Ease of implementation (4.2.5), Human Health (4.2.6) and Environmental awareness (4.2.3). Chapter 4.3 (Recycling of marine plastic debris) will give a short introduction to the technological possibilities of the recycling of mixed plastics and the properties and difficulties regarding marine plastic debris recycling.

In chapter 5, basic calculations are made for a plastic debris collection with on-board gasification in a fluidized bed reactor designated for three different forms of plastic concentrations on the water surface. First results of the mass flow and product yield of collected plastics and gasification products as well as fuel savings are given.

4 Problem description

The general problem about marine plastics is their persistency. This property causes accumulation of plastics in the marine environment. Even though there is degradation, plastics only brake into smaller pieces, but do not exit the ecosystem (Cooper and Corcoran, 2010). This chapter focuses on the current knowledge of the consequences connected to marine plastic, the sources and sinks of marine debris, its distribution and composition, the properties of marine plastic as well as different recycling methods for plastic collected in marine environments.

Chapter 4.2 reflects the different concerns regarding marine plastic debris and other reasons for collection and recycling, whereas chapter 4.3 and 5 present a possible solution for these concerns, in particular for collection and recycling.

4.1 Definition, source and distribution of marine plastic debris

Marine plastic debris is defined as the plastic that entered the marine environment and is not of any use to us any more. In other words, marine plastic debris is plastic waste in marine environments. Estimates of marine plastic debris floating in the ocean vary between 7 000 – 35 000 t (Cózar et al., 2014a), 236 000t (van Sebille et al., 2015) and 268 940 t (5.25 trillion plastic items) (Eriksen et al., 2014). In the Mediterranean sea alone, 1 000 - 3 000 t floating marine plastic are expected (Cózar et al., 2015). And these only constitute “1% or less of the amount of plastic waste available to enter the ocean annually from land-based sources” (van Sebille et al., 2015, p. 9). The term **marine debris** or **marine litter** means waste generally found in marine environments and includes other materials, like glass and metal. **Marine environment,** in this context is defined as oceans, as well as coastlines close to the water, such as beaches. The composition of marine litter varies greatly and papers differentiate materials only roughly. Plastic makes up a percentage of about 50% of all items ((43% (Kordella et al., 2013), 42.5% (Thornton and Jackson, 1998), 88% (Mobilik et al., 2015), 47% (Zhou et al., 2011)). Some researches discriminate different kinds of plastic like foamed plastics, hard plastics and items that occur very frequently in a sample (e.g. nylon) (S. L. Moore et al., 2001, p. 243; Topçu and Öztürk, 2010, p. 303). Quantities are indicated in items/km^2 or in kg/km^2. Analyses of marine debris are only done small plastic particles (Enders et al., 2015; Morét-Ferguson et al., 2010; Song et al., 2015). Some authors define **microplastic** as primary or secondary plastic fragments smaller than 5 mm (Moore, 2008; Wright et al., 2013). They are collected with a neuston net that has a mesh size of 0.33 mm (Eriksen et al., 2014). However, recent papers further differentiate in mesoplastic, microplastic (<1mm and >1 µm) and nanoplastic (Andrady, 2015). Nanoplastics are defined as being smaller than 100 nm (Koelmans et al., 2015) (see Figure 1).

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Figure 1 „Size matters. Suggestion of plastic debris nomenclature based on size, as proposed by the European MSFD technical subgroup on Marine Litter (MSFD GES Technical Subgroup on Marine Litter, 2013). The overall term "microplastic" is composed of small microplastics (SMPs, smaller than 1 mm) and large microplastics (LMPs, 1 - 5 mm), to differentiate between two commonly used definitions of microplastics"(Van Cauwenberghe et al., 2015).

About 48% of the microplastics consist of Poylethylen (PE) und Polypropylene (PP) and have a lower density than seawater (Enders et al., 2015, p. 75) (Table 1). Some of the "microplastic" particles samples have turned out to be paint particles, presumably from ship hulls (Morét-Ferguson et al., 2010; Song et al., 2015; Turner and Solman, 2016). Many of the microplastics analysed, about 40%, are attributed to fibres (Enders et al., 2015). However, the number of samples analysed is very low, so none of these studies can give a representational composition of the different marine plastic materials. Nanoplastics (<100 nm) cannot even be detected with state of the art technology (Koelmans et al., 2015).

Marine debris is not evenly distributed in the ocean, but it can be found in different concentrations at varying depths, mostly due to different densities of the plastics (see Table 1). Strafella et al. (2015) found the highest plastic concentration (171 ± 36 kg/km^2) in 30 m depth near the coastline (Strafella et al., 2015). According to Lattin et al. (2004) the highest plastic concentration is on the bottom of the ocean, compared to the middle and top part of the water column. Surface plastic concentration is lower than at the bottom, but higher than in the middle part of the water column. Microplastics have other distribution patterns compared to bigger fractions (Enders et al., 2015).

Low density plastics and plastics with air bubbles can be transported over long distances. Models of the ocean currents show that the five subtropical ocean gyres accumulate plastic (Lebreton et al., 2012; Maximenko et al., 2012). Nevertheless, 50% of all microplastics are in regions with a lower microplastic concentration (van Sebille et al., 2015, p. 7). Unlike Maximenko et al. (2012), who begin their simulations with a homogenous distribution, Lebreton et al. (2012) (see Figure 2) starts with certain sources of debris on land (80%) and offshore (20%). They consider population density and define coastal release points and important commercial shipping lanes. The best explored of the five gyres is the North Pacific Central Gyre (Lusher, 2015), also known as „Great Pacific Garbage Patch" (Kaiser, 2010).

Table 1 Different densities of polymers in comparison to seawater and sediment (after (Enders et al., 2015; Löder and Gerdts, 2015).

abbreviation	material	density [g/cm³]	
EPS	Expanded polystyrene	<0.05	low density polymers
PP	Polypropylene	0.85–0.92	
EVA	Ethylene vinyl acetate	0.92-0.95	
	Silicone	0.8	
LDPE	High density polyethylene	0.89-0.93	
HDPE	High density polyethylene	0.94-0.98	
	Seawater	1.02-1.029	
PS	polystyrene	1.04-1.06	high density polymers
ABS	Acrylonitrile butadiene styren	1.04-1.08	
PA	Polyamide	1.12-1.15	
PMMA	Polymethylmethacrylate	1.16-1.2	
PC	Polycarbonate	1.2-1.26	
PU	Polyurethane	1.2-1.26	
PET	Polyethyleneterephthalate	1.38-1.41	
PES	Group of polyesters	1.10-1.4	
PVC	Polyvinylchloride	1.38-1.41	
PTFE	Polytetrafluoroethylene	2.1-2.3	
	Sediment	2.65	

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Figure 2 Accumulation of surface marine debris after 30 years with different scenarios (a-c) (percentage of total particles introduced) and boundaries of the various accumulations zones (d) (Lebreton et al., 2012)

In general, more marine plastic debris can be found on the northern hemisphere than on the southern hemisphere (Lebreton et al., 2012; van Sebille et al., 2015, p. 7). 56% of all marine plastic are expected in the northern hemisphere (Eriksen et al., 2014).

There are also models that are based on actual measurements of marine debris concentrations (Cózar et al., 2015, p. 5; Eriksen et al., 2014; van Sebille et al., 2015). The actual size of these “garbage patches” (accumulation zones) is still disputed. The North Pacific Subtropical Gyre is created by four currents which move clockwise around an area of 20 million km^2 (“Great Pacific Garbage Patch - National Geographic Education,” n.d.). Simulations of the Mediterranean currents (http://plastics.cmcc.it/files/DFG_suppl.mov) by Liubartseva et al. (2016) show a seasonal variation of the floating debris concentration. In the simulation of Liubartseva et al. (2016) marine debris releases into the ocean double every decade to mimic growth of global consumption and waste production.

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Figure 3 Modelling results of the global density of marine debris in four different fractions (0.33–1.00 mm, 1.01–4.75 mm, 4.76–200 mm, and >200 mm) (weight-density g/km^2) (Eriksen et al., 2014).

These models are still to be improved, for example, the model of Eriksen et al. (2014) (see Figure 3) only comprises 0.1% of the global annual production (Eriksen et al., 2014). Theoretically, the smaller the plastic fractions are, the more the number of plastic items is expected to increase, if the masses stay constant, but measurements and models do not correspond with the theoretical assumptions. Scientists speak of a “**missing fraction**” of small micropastics (Cózar et al., 2014a; Enders et al., 2015, p. 80). This is explained by an unknown sink or acceleration of degradation of the fractions smaller than 4.75mm, especially around 2.2 mm (see Figure 4). Thompson (2015) expects most of the particles to be at the bottom of the deep sea (Thompson, 2015).

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Figure 4 The missing fraction of small micro plastics seen in the size distributions of plastic fragments by ocean basin (Cózar et al., 2014b).

Another reason why models have difficulties in depicting reality is that data quality and resolution of different samplings vary strongly (Löder and Gerdts, 2015). Sampling results cannot be directly compared (Lusher, 2015). Sampling on water surface is conducted with manta trawls or neuston nets (Figure 5) at speeds between 1 and 5 knots (1 kn = (1852/3600) m s^{-1} (Generalic, 2017)). The concentration of seston- plankton, jellyfish or red tides influences sampling volumes. Bigger quantities can be filtered from a mesh size of 300 µm and above, smaller mesh sizes are rarely used because they become blocked easily (Löder and Gerdts, 2015). For an overview on the different approaches used for sampling, see Table 2.

Table 2 Overview on different sampling methods used for marine plastic sampling.

Mesh-size	Net measurements	depth	speed	type	refereces
280 µm	opening: 127 mm^2	10 m	-	-	(Thompson et al., 2004)
40 mm	length (codend): 2.7 m	8-100 m	5.5 knots	rapido trawl, a modified beam trawl	(Strafella et al., 2015)
0.333 mm	opening: 16x61 cm	surface	1-1.5 m/s	-	(Roos Lundström and Måartensson, 2015)
0.333 mm	0.9×0.15 m^2 rectangular opening manta trawl length: 5 m collecting bags: 30×10 cm^2	5 m	1-2.3 m/s	-	(Lattin et al., 2004)
0.505 mm	opening: 30 cm (depth)x50 cm (width)	10 - 15 cm	1.5-2 knots	Sameoto Neuston Net	(Doyle et al., 2011)
0.505 mm	opening: 15.5 cm (depth)x86 cm (width)	10 – 15 cm	-	Manta net	(Doyle et al., 2011)
0.505 mm	71 cm diameter	up to 212 m	1.5-2 knots	Bongo sampler	(Doyle et al., 2011)
0.333 mm	opening: 0.9 x 0.15 m^2 length: 3.5 m Collecting bag: 30x10 cm^2	-	1 m/s (0.5-1.5 m/s)	-	(C. J. Moore et al., 2001)
0.2 mm	opening: 1x0.5 m	surface	2-3 knots	neuston net	(Cózar et al., 2015)
200 µm	opening: 1x0.5 m	0.25 m	2-3 knots	neuston net	(Cózar et al., 2014a)
333 micron net	opening rectangular 0.9x0.15 m^2 (manta net) 61 cm (bongo net) 31 cm^2	5 m, surface, aprox. 30 m	1-2.3 m/s	Manta trawl Bongo net (mid depth samples) Epibentic sled (bottom samples)	(Lattin et al., 2004)
20 mm GOC 73), 40 mm (OTMS) with an outer cover of 12 mm	-	85 - 3 000 m	-	GOC 73 net and otter trawl Maireta System (OTMS) as well as imaging technology (still photograph and video)	(Pham et al., 2014)
150-µm	mouth 80x30.5 cm	surface	4-5 knots	Kahl Scientific model neutston net	(Wong et al., 1974)
330-µm	mouth: 50x50 cm, side length 3 m	surface	2 knots	neuston net	(Yamashita and Tanimura, 2007)

Figure 5 operating Neuston catamaran (a) und manta trawl (b) (Löder and Gerdts, 2015).

There are different sources of marine debris. One can differentiate between land-based and ocean/waterway-based debris sources (Sheavly and Register, 2007, p. 2). Land-based debris consists of litter and debris, washed and blown away from beaches, streets and parking lots. It mostly enters the ocean through sewers, whereas the ocean/waterway-based debris is lost from ships and offshore platforms. It is estimated that in 2010 only, 4.8 -12.7 million tonnes of marine plastic have entered the oceans (Jambeck et al., 2015). Figure 6 illustrates that the most marine debris is produced by China, followed by Indonesia, the Philippines, Vietnam and Sri Lanka because of the waste management in these countries. Especially in low income countries, less than 50% of debris is collected (Hoornweg and Bhada-Tata, 2012, p. 8). There is a positive correlation between economic development, urbanization and waste production (Hoornweg and Bhada-Tata, 2012). Therefore, especially developing countries without an effective waste management, but with rising incomes are at risk to be a major source of marine waste.

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Figure 6 Quantities of estimated mismanaged plastic waste (million tons) generated in countries close to the shore (50km) in 2010 (Jambeck et al., 2015).

4.2 Reasons to remove and recycle marine plastic debris

Why is there a need to remove and recycle marine plastic debris? One may argue that ‘it simply does not belong into the environment´ (“Plastik hat in der Natur nichts verloren”.) as mentioned by Wilhelm Vogel at a panel discussion about marine microplastics. Or because we need to apply the precautionary principle (Felt et al., 2017). However, none of these statements do really help in deciding which measures have to be implemented and where the actual problems lie. Doing something against marine plastic, in whatever way means some sort of effort and investment of financial resources. In order to help in deciding how much effort and resources are to be used, the different arguments are structured into six “reasons for debris collection and recycling”. These reasons are simply negatively rated or problematic facts about marine plastic debris, found in various literature (chapters 4.2.1-4.2.4) and other reasons for the choice of this instrument (4.2.5 Ease of implementation and 4.2.6 Environmental awareness).

The reasons for debris collection vary greatly. Firstly, coastal regions with a lot of tourism will collect debris from beaches for **aesthetic reasons**. Secondly, cleaning activities are undertaken to **protect habitats**. Thirdly, there are diverse views on marine plastic debris in connection with **human health**. Fourthly, **fishing** efficiency is reduced by marine debris. Fifthly, technological solutions, like litter collection and recycling facilities, are favoured policy instruments because they can be **implemented** relatively easily (MKinsey Center for Business and Environment, 2015) and measurable outcomes are achieved. Sixthly, an increase in environmental **awareness** of the population is desired as environmental awareness is associated with an ecofriendly behaviour and acceptance of measures focusing environmental targets. Awareness, therefore, shall be increased by all kinds of activities, campaigns, commitments and laws including debris collection.

4.2.1 Aesthetics

Having a clean ocean and beach is a very important reason for clean-ups. Balance et al. (2000) used the travel-cost method to estimate the recreational value of all beaches of the Cape Peninsula. Clean beaches in this region are worth 9-50 million ZAR (1.3-7.4 million USD) (Ballance et al., 2000) (1 ZAR = 0.14717 USD; May the 1st, 2000 (OANDA, 2017)). Constraints in tourism activities caused by marine debris already are an issue for many countries, even though no studies have been conducted in most cases to support this. One example is the South Korean Geoje Island, where a river caused severe pollution with marine debris on beaches in the summer vacation season. The consequences were a decrease in the number of visitors, as well as in expenditures on daytime activities altogether resulting in a loss of 29–37 million USD (Jang et al., 2014).

The main aspects beach users value are, amongst others, no litter, followed by safety, facilities, water quality and scenery (Williams et al., 2016). Part of the debris on beaches (e.g. cigarette butts) is scattered by the beach users themselves (Martinez-Ribes et al., 2007). Kordella et al. (2013) stated that at 70% of all surveyed beaches in Greece, recreational activities, onshore or close to the shore, were the most prominent litter sources. Therefore, collection at hot spots of plastic concentration offshore, like, at one of the subtropical ocean gyres, will not have visible effects on the aesthetics of coastal areas.

4.2.2 Habitat and wildlife protection

The protection of habitats and the wildlife are one of the most common arguments for cleaning activities. Plastic is particularly potentially harmful to animals because of its persistency. Animals may become **entangled** in plastic ropes and other plastic items. There is no estimate on the total number of entangled animals, but animals across all species are affected (Kühn et al., 2015). Furthermore, plastic resin pellets and plastic bags are **ingested** because of their visual similarities with fish eggs and jellyfish respectively (Moore, 2008). So called “**ghost fishing**” does not have any influence on fishing mortality (Revill and Dunlin, 2003), but on the population of turtles (Wilcox et al., 2015). Stranded plastic influences the heat transfer of the sand. With a plastic concentration of 1.5%, the maximum temperature drops by 0.75°C, which causes the number of hatched female sea turtles to fall (Carson et al., 2011). Tests with lungworms exposed to sand with 5% microplastic containing pollutants showed biological effects like reduced resistance to bacteria or increased mortality (Browne et al., 2013).

Vegetation is also affected by debris. This effect is called **smothering** and describes weight and shading effects of debris which inhibit plant growth. Mangrove forests are particularly affected as debris covers the ground and seedlings are smothered (Kühn et al., 2015).

Because of its persistency and buoyant properties, marine plastic debris is a vector for **invasive species**, which may influence the ecosystem (Gregory, 2009) (**rafters**). This colonization of organisms varies between the floating objects, depending on the buoyancy, surface rugosity and floating behaviour. Rafting on abiotic substrata is only possible for a limited amount of species due to nutrition and the lack of oxygen whenever the object turns around (Bravo et al., 2011). If the organisms survive their journey and settle down, they may reproduce at a place they could never have reached on their own (Kiessling et al., 2015).

4.2.3 Human Health

Direct threats to human health are limited to injuries and diseases like mycosis (Ivar do Sul and Costa, 2007). More important in this context are the indirect health effects.

Plastic particles with a size less than one mm can be taken in by plankton eating animals and thus enter the food chain (Moore, 2008). Indirectly, those tiny particles are a risk to human health as well, if they accumulate in the food chain. As of today, there is no evidence that they do accumulate (Rochman, 2015). Mesopelagic fish are estimated to ingest 12 000-24 000 tonnes of plastic debris per year in the North Pacific Subtropical Gyre alone (Davison and Asch, 2011). This and reports on microplastics found in fish and other ocean inhabitants implies a potential trophic transfer (Lusher, 2015). In spite of that, there is no evidence that microplastic enters the human body through nutrition. However, certain substances like bisphenol A (BPA) can leach from polycarbonates into food and the human body. In the body, BPA can be mistaken for a hormone and can cause several diseases (Galloway, 2015; Yang et al., 2011). BPA is a phthalate-based plasticizer, which has been used since the 1920s and is a major component of PVC (Oehlmann et al., 2009). The production of PVC overall requires the most additives of all plastics (73% of the global production) (Galloway, 2015; Tanaka et al., 2013).

Polybrominated diphenyl ether (PBDE), used as flame retardant, has been found in sea birds. The additive thereof is assumed to be able to transfer into the tissue through nutrition (Tanaka et al., 2013). “Some PBDE congeners are categorized as persistent organic pollutants (POPs)” (Tanaka et al., 2013). Persistant, toxic and bioaccumulative chemicals with adverse effects on human health or the environment are regulated in the Stockholm convention on persistent organic pollutants and are referred to as **POP**s (UNEP (United Nations Environment Programme), 2009). The majority of polymerisation chemicals, like solvents, catalysts or additives, are most hazardous (Lithner et al., 2011). Plastic polymeres are generally inert, nevertheless not all polymerisation reactions are complete. Because of this, unreacted, hazardous residual monomeres can enter the environment (Lithner et al., 2011). Polyurethan (PUR), which can be found in PUR flexible foam, is placed as number one in an environmental and health hazard ranking by Lithner et al. (2011) because it has two carcinogenic as well as germ cell mutagene and one very toxic monomere. Plastics, do not only contain POPs themselves, but they are shown to absorb them from the water as well (Andrady, 2011) (**passive samplers**). Gouin et al. (2011) describe this process with a thermodynamic approach: From the moment, the volume ratio of polyethylene is high enough, compared to the ratio of carbon present in the system, it is possible that chemicals are partitioned and absorbed into it. When polyethylene is present in the intestinal tract, a reduced body burden concentration could occur because of the high sorption affinity of polyethylene (Gouin et al., 2011). Thus, “Microplastic ingestion may either clean or contaminate the organism, depending on the chemical fugacity gradient between ingested plastic and organism tissue” (Koelmans, 2015).

There is also the possibility of toxic metals to be leached out from marine plastic debris into the beach environment. Most of the lead (Pb) contained in debris on beaches is contained in PVC, but Nakashima et al. do not consider the concentrations found harmful to the environment (Nakashima et al., 2012).

4.2.4 Fishing efficiency

Fishery is directly affected by marine debris. Efficiency in fish catches is reduced because debris accumulates in the nets and makes them more visible to the fish. Therefore, nets have to be cleaned from the debris. Another cost factor is litter getting stuck in the propellers of fishing vessels or fishing gears being damaged (Strafella et al., 2015). Due to high debris concentrations, fishermen even need to avoid certain areas or change their fishing behaviour (Nash, 1992). Besides the protection of the marine environment and safety, inefficiency in fishing was one of the main arguments for the Marine Debris Management Program in South Korea to remove marine debris from beaches, the water surface and the deep seabed (Cho, 2011). The removal of litter was conducted by fisherman, resulting in some contradictions regarding the ´polluter pays'-principle, as one of the projects was called "removement of derelict fishing gear". The program paid fishermen for removing the debris they produced themselves (Jang and Song, 2013).

Collection on the sea surface alone, which is the focus of this work, cannot completely restore fishing efficiency. Usage of trawl nets is still affected by marine debris as the majority of the debris lies at the bottom of the sea (see chapter 4.1).

4.2.5 Ease of implementation

This chapter provides an overview on the different policy instruments used to tackle the problem of marine debris, and the problems regarding the implementation of these instruments. Different measures, like economic instruments and technical solutions, will be compared. Ease of implementation may not be the reason for implementing measures against marine plastic debris, but it has a major influence upon the decision in favour of collection.

International regulations oblige all participating states to do everything necessary at national level to meet the specific goals of the agreements. There are various kinds of regulations with different topics, some of which tackle marine debris. Their overall goal is "zero waste discharge". One of the first international instruments which handled marine litter was the International Convention on the Prevention of Pollution by Garbage from Ships, established in 1973 (MARPOL, Annex V (1988)), in force since 1983 (IMO (International Maritime Organization), n.d.). Later, in 1974, the Regional Seas Program was initiated and has already been signed by over 140 countries

(UNEP, 2005). Other declarations followed (see Table 3) and there are lots of regional regulations and management plans which also treat marine plastic litter directly or indirectly. All of these instruments focus on either prevention or cleanup (McIlgorm et al., 2011).

Table 3 Management instruments tackling marine debris, incomplete list

Instrument	International /regional	In force since	references
Annex V of MARPOL 73/78	international	1983; latest version 2013	(Chen, 2015; IMO (International Maritime Organization), n.d.; Ryan, 2015)
London Protocol (LP) Convention on the Prevention of Pollution by Dumping of Wastes and Other Matter	international	1972, amended 2006	(Chen, 2015; London Protocol, 2006)
United Nations Convention on the Law of the Sea (UNCLOS)	international	1994	(Chen, 2015; UN, 2013)
UNEP Regional Sea Programme and Global Programme of Action (GPA)	international	2003	(Chen, 2015)
United Nations Environment Programme (UNEP) and intergovernmental Oceanographc Commission (IOC): Guidelines for study design and monitoring of marine debris	international	-	(Chen, 2015)
United Nations Environment Programme (UNEP): Honolulu Strategy, Honolulo Commitment	international	2012	(Ryan, 2015)
United Nations Environment Programme (UNEP): Global Partnership of Marine Litter (GPML)	international	2012	(Chen, 2015)
United Nations Environment Programme (UNEP): Regional Sea Programme (RSP)	international	2005	(Chen, 2015; UNEP, 2005)
EU 2008/56/EC Directive on establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)	regional	2008 (implementation until 2010)	(Chen, 2015; EU Meeresstrategie-Rahmenrichtlinie, 2008)
EU directives on waste management of land-based waste	regional	-	(Chen, 2015)
Commission for the Conservation of Antarctic Marine Resources (CCAMLR) (Marine Debris Program)	regional	1982	(CCAMLR, 2016; Chen, 2015)
Annex IV of the Helsinki Convention	regional	1992	(Chen, 2015)
Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention)	regional	1976; amended 1995	(Chen, 2015)
Convention for the Protection and Development of the Marine Environment in the Wider Caribbean Region (WCR) (Cartagena Convention)	regional	1986	(UNEP, n.d.)
Assessment & Management of Environmental Pollution (AMEP)	regional	-	(UNEP, n.d.)

The goals of all these plans, programs and strategies are convincing, and they certainly work in theory; however, the question arises as to why marine plastic litter is still entering the oceans (see chapter 4.1)? The intentions do not seem to be the problem and states are well aware of the sources of marine debris, but the implementation of the measures is not effective. "IMO was established to *adopt* legislation. Governments are responsible for *implementing* it. When a Government accepts an IMO Convention it agrees to make it part of its own national law and to enforce it just like any other law" (IMO (International Maritime Organization), n.d.). This is not only the case for the IMO Convention, but for every international agreement too. So, the effectivity of these international agreements is only guaranteed if the countries do implement measures at regional and national levels. This has, for example, been done by the United States (US) in the Marine Plastic Pollution Research and Control Act (MPPRCA) (1987), the United Kingdoms (UK) with its Merchant Shipping (Prevention of Pollution by Sewage and Garbage from Ships) Regulations (2008), or the Merchant Shipping and Fishing Vessels (Port Waste Reception Facilities) Regulations (2003) (Chen, 2015).

First successes have already been achieved, such as reductions in ship-based litter in Australia's southern oceans, as agreed in MARPOL (Edyvane et al., 2004), but still numbers of entanglements of animals do not seem to have fallen (McIntosh et al., 2015).

Some countries have their own regulations that may surpass the obligations of international instruments. Despite of the fact that, even though there is a huge variety of instruments, most countries do not oblige themselves or measures are ineffective because there are neither control nor penalty (Chen, 2015).

Governments can devise different instruments to implement international agreements. There are the typical **command and control** measures, also called "laws", which ban or limit certain materials or behaviour, such as the ban of microplastic in cosmetics that is discussed in Austria, Belgium, Luxembourg, the Netherlands and Sweden, for example (Buxton, 2016; PK-Nr. 537/2015, 2015). Command and control instruments are indispensable, especially for the prevention of illegal dumping (Newman et al., 2015).

Furthermore, there are **economic instruments**. They work differently than command-and-control measures. Economically speaking, costs of waste management are externalized by discharging waste directly or indirectly into the sea. As oceans are neutral territory, marine debris only becomes a problem for a certain country once it is washed ashore (McIlgorm et al., 2011). Direct costs of litter in the Asia-Pacific region are estimated at about 1,26 billion USD (McIlgorm et al., 2011). Economic instruments can influence waste generation at a consumer and producer level. Economic instruments are taxes, fees, refund systems, penalties, compensation schemes, tradable permits and incentives. More about market based instruments can be found in the „Guidelines on the use of market-based instruments to address the problem of marine litter" (UNEP, 2009), “Economic instruments and marine litter control” (Oosterhuis et al., 2014) and Newman et al. (2015). Both, command-and-control as well as economic instruments, are harder to implement than the following “soft”-regulation and the technological approach.

Another instrument is **“soft” regulation** (EU Comission, 2016). That is where business and industries do self-regulation. Two examples are the Operation Clean Sweep (Ryan, 2015) and The Declaration of the Global Plastics Associations for Solutions on Marine Litter (Marine Litter Solutions, n.d.). The Extended Producer Responsibility (EPR) (OECD, n.d.) specifically targets treatment or disposal of post-consumer products and aims to make producers responsible. Soft regulation is cost-efficient and faster than mandatory requirements. Furthermore, it is flexible and can be easily adapted to technological changes and market requirements. Co-regulation monitoring and sanctions by the legislator complement the self-regulation (EU Comission, 2016). Involvement of the producer is essential as the product design can help to reduce its recyclability and health risks.

Information is also considered as an instrument. Effects of information are discussed in chapter 4.2.6 (Environmental awareness). This chapter also explains “nudges”, a way of influencing behaviour through architecture of decisions.

Waste management infrastructure is one of the most important measures against marine plastic debris. With a well-established waste management, plastics are more likely to be recycled after usage and not to litter the environment (see also chapter 4.2.6). Waste management is a **technological approach** to combat marine plastic. Technological approaches do not change waste generation, but make waste management more efficient and they also create benefits, such as energy and heat production. Figure 7 emphasizes that they are easier to implement as compared with fees or bans and are, moreover, economically attractive. Technological approaches are always related to some sort of investment in facilities. For instance, debris is generally collected in a country, but there are not enough bins on the streets, they are already full and people start putting litter on top of the bin, where it can be easily blown away by the wind. Applying the technological approach, one would suggest to empty bins more often or to place more bins in the streets. An additional measure for better waste management would be to change from landfilling to waste incineration or gasification. In the first case, the necessary investment is really low; only a few bins or personnel are required. In the second case, acquisition costs are higher. These additional costs may be the reason why in some countries, waste infrastructure is very poor (see chapter 4.1). Nevertheless, it is important to invest in state-of-the-art technology in order to maximize efficiency of waste treatment.

Having an offshore waste collecting and recycling facility would also be a technological approach with advantages and disadvantages as described. The most important advantage is that it would be easier to implement than most of the other instruments described. Moreover, the effects of this measure are easily quantifiable and can be used for monitoring and evaluation.

For the original figure see referenced paper or printed version of this thesis at the library of the University of Natural Resources and Life Sciences, Vienna.

Figure 7 Different net benefits ($/t waste leakage reduced) and implementation difficulty for measures (MKinsey Center for Business and Environment, 2015)

4.2.6 Environmental awareness

Urban (1986) describes three cognitive dimensions of environmental awareness on a **personal level**: 1) environmentally relevant values - evaluative part ("umweltrelevante Wertorientierung"),
2) environmental attitude - affective part ("umweltbezogene Einstellung") and
3) willingness to commit - conative part ("Handlungsbereitschaft") (Urban, 1986).

Actual environmental commitment will only happen if a person shows willingness to commit by oneself. Valuing the importance of environmental measures or having a high opinion on these measures alone will not lead to actions regarding the protection of environment or a change in behaviour as long as no willingness to do so is shown. Furthermore, there are socio-demographic variables (duration of schooling) and socio-ecological variables (considering environmental impacts as negative) which influence the willingness to commit (Urban, 1986).

A study of Umuhire and Fang (2016) indicates the same results with regard to ocean

environmental topics. Umuhire and Fang (2016) define “components of ocean environmental concern” as: perception (features 1-2), ocean environment knowledge which represents understanding (features 3-4) and participation in ocean-related activities (represents action) (feature 5).
They base their study on five features of ocean environmental awareness: “(1) a concern for the state of the marine environment; (2) recognition of a safe and healthy marine environment as socially valuable; (3) an ability to identify the sources of marine environmental threats; (4) an understanding of the necessity to take personal part in prevention, protest, creation, and other collective actions about the oceans; (5) a readiness to take personal part in the marine environment concerned actions” (Umuhire and Fang, 2016). In Table 4, the personal and external/social level of ocean environmental awareness are summarized.

Students at Xiamen University were found not to have a high level of knowledge of the oceans, although this university also has a department of Oceanography and 70% of the students take related courses. Only 8% were involved in students´ organizations related to the oceans issues, thus taking actions themselves to improve the environmental situation (Umuhire and Fang, 2016). Yet the study shows that knowledge about the environment and ocean helps to dramatically increase the willingness to participate in marine environmental protection issues (Umuhire and Fang, 2016). Because of that, awareness-strategies in combination with proper solid waste facilities are recommended for litter reduction (Kordella et al., 2013).
Furthermore, there are other cases of creating awareness on a personal level, like design ideas from architects („Plastic Island“ (Eilander Architects, 2010)) and designers (The Garbage-Seascraper (eVolo Architecture Magazine, 2014)) which tackle the problem. These ideas primarily influence the personal level of environmental awareness. They approach people who are interested in design and make them think about the issue and support the formation of opinions and values. Some ideas get past scratching and are actually already in development, with the help of private crowd funding and social media, like the „Ocean Cleanup“ (ocean cleanup, n.d.) and the Seabin Project (Ceglinski and Turton, n.d.). Giving financial support for a concept of a possible solution to the problem can be considered as a commitment that does not involve a change in behaviour.

Table 4 Overview on the two different levels of ocean environmental awareness (after (Umuhire and Fang, 2016; Urban, 1986)

personal level (3 cognitive dimensions)		**external/social level**
evaluative	concern for the state of the marine environment; recognition of a safe and healthy marine environment as socially valuable	deconstruction of barriers for taking action, creation of opportunities
affective	ability to identify the sources of marine environmental threats; an understanding of the necessity to take personal part in prevention, protest, creation, and other collective actions about the oceans	
conative	readiness to take personal part in the marine environment concerned actions	

Conventions like MARPOL Annex V are said to raise the awareness of the problems related to marine debris (Edyvane et al., 2004). Following the concept of different aspects of environmental awareness made by (Urban, 1986) conventions and new international and national organisations address the **external and social level** of environmental awareness. In general, they are important for social integration of environmental awareness and make decisions easier to legitimate (Urban, 1986). For example, having a good regional waste management makes it easier to dispose waste correctly. Good environmental behaviour is supported or triggered when there are no barriers against it (Urban, 1986). In addition, organizing voluntary beach cleaning activities will give people the opportunity to commit themselves.

The U.S. legal scholar Cass Sunstein and the influential behavioral economist Richard Thaler describe "**nudges**" (Leonard, 2008; Wallace-wells, 2010) as a way the government can influence the personal decision of an individual in order to architect the choice it gives people. In the context of plastic, this could, for example, be implemented to reduce the amount of consumed shopping bags. The economic approach would suggest a fee for shopping bags instead of having free bags. Applying command and control instruments, the state would ban the use of plastic bags in shops. This is not necessary when implementing "nudges". Here, it would be sufficient to change the situation at the cash desk, from people automatically receiving their items in a free plastic bag to asking people whether they need a bag or not. Chances are higher that people will not take a bag if they have to decide.

Not only governments can influence environmental awareness, but also companies. When **companies** claim themselves sustainable and launch marketing initiatives like labelling, they can build awareness of particular properties of different products. The consequences of this awareness are not always intuitive as the model of Galbreth and Gosh (2013) shows. Differentiation, for example in form of labelling, can lead to a reduction in competition, and companies which are rated as “not sustainable” may also have increased profits (Galbreth and Ghosh, 2013). Whether a person decides to buy a “sustainable” product or not is related to a person’s self-definition, as a person may identify himself or herself with a company (Bhattacharya and Sen, 2003). In the context of marine plastic debris there is, for example, the “ecover” product line. The name of this label already suggests, that the packaging is made out of recycled marine plastic debris (ecover, n.d.) from the “Plastic Whale”-project in Amsterdam (Plastic Whale, 2016).

A lack of awareness of marine plastic debris related issues is strongly influenced by the missing knowledge of the issue. Knowledge about the environment, the problems of marine plastic debris and its sources, is not synonymous with actually thinking about what possible actions and taking action (willingness to commit). Still, every measure will influence a person’s values, attitude and behaviour in some way. The influence on environmental awareness of a flexible collection and recycling facility on a **personal level** is limited to the information passed on to the population because collection will take place offshore and people will not be confronted directly with the facility as they live onshore. This information can include possibilities of recycling marine plastic, as well as collected quantities, locations and estimated sources of plastic debris, so that people get an idea of the scope of the problem.

It is not clear how a recycling ship influences the **external and social level** of the environmental awareness. But it is possible that with a working monitoring tool, countries with a high leaching potential (as described in chapter 4.1) can implement waste-management more easily. Simple cleaning of the ocean without any monitoring function on a large scale, can have a reverse effect. Being aware of an offshore collection system may even trigger further leakage and prevent investments in waste management.

If you imagine having a perfect collection facility which can entirely clean all the oceans from plastic within a few years and at bearable costs, what massage does this send to countries that have to decide whether to invest in waste management and reduction or not? This work made clear, such a facility is not realistic at all, but this gedankenexperiment helps to see the problem of marine debris collection. Considering, that high investments are generally avoided if not absolutely needed, the favoured option for the responsible person in this experiment would be to use the waterways as free disposal and transport waste in this way into the oceans where it would be collected anyway (free-rider problem). This option would be economically attractive because no investment into waste management needs to be made. Furthermore, because of the perfect collection in the oceans, waste is still collected and treated.

Now think of a second case, but instead of a complete cleaning, let us assume a small collection facility which registers all debris collected. This information is then used to feed simulation tools to locate the sources of the debris, like the one Yoon et al. (2010) developed for the Japan Sea. In this way the polluter-pays-principle could be applied. Facing high penalties and international pressure has a strong effect on external and social environmental awareness because it makes implementation of a better waste management or instruments for waste reduction much easier. The essence of these thought experiments is that if we cannot clean the oceans entirely, we should not imply to anyone that we could. This would only lead to a delay in implementation of instruments that tackle waste generation or management. Instead, we should only use measures that support environmental awareness in a positive way.

4.2.7 Summary

Even though there are huge knowledge gaps, it can be said that marine plastic debris is certainly changing the marine ecosystem. We have to cope with this change and there are different approaches.

Compared to other instruments, the technological approach of marine plastic debris collection and recycling is easy to implement (see Figure 7). Since the presence of marine plastic debris influences the ecosystem in different ways with negative effects on biodiversity, aesthetics, fishery and health, the logical conclusion would be that the removal of the debris will also remove the negative effects. Currently, not all risks and problems can be avoided using collection technology. Collection at sea will not replace collection at beaches with lots of tourism, as most of the beaches are littered by the beach users themselves (Kordella et al., 2013) (see chapter 4.2.1). Cleanings at the bottom of the sea are impossible or too expensive to carry out on a large scale, so the fishing industry will still have to deal with debris when using trawl nets (see chapter 4.2.4). The same is true for wildlife, as a reduction of debris in hotspots will not prevent animals from encountering marine plastic debris in general. Literature identified several concentration levels of plastics and contained substances that would have major effects on the ecosystem. For example, sand may be contaminated with microplastic (Browne et al., 2013), the lead which is contained in PVC may leach out into the beach environment (Nakashima et al., 2012) and the sea turtle population may be affected by large amounts of plastics that influences on the heat transfer of the sand (Carson et al., 2011) (see chapter 4.2.2 and 4.2.3).

Most health risks are associated with microplastic and up to the present day, there is no way to remove them from the sea on a large scale. Furthermore, nanoplastics, being even smaller than microplastics, are not measurable. There are no studies which estimate how long it takes for a plastic bottle or a plastic rope to entirely fragment into microplastics because of the long timescales. Nevertheless, it is obvious that fragmentation occurs and that plastic is in sea for several decades already. The reduction of bigger and removable plastic in the sea can reduce the increase of microplastic in the future produced through degradation.

Nevertheless, any removal will be of little or of no avail and effects will not show, until the sources of marine plastics are eliminated. Sources of marine plastic, such as fishery, incorrect waste disposal on land and at sea, plastic fabric particles in the wastewater as well as natural disasters like floods or strong winds, imply that inputs can only be reduced, but never stopped completely. Jang and Song criticize that the main emphasis of the South Korean Basic Plan to Manage Marine Debris (2009 -2013) is on debris collection, which does not support the polluters-pay principle (Jang and Song, 2013). Most scientists claim that the removal of marine debris means „treatment rather than cure“ (Newman et al., 2015). Litter removal is an important action against the problems associated with marine plastic debris but does not have to be the only one. The Regional Action Plan (RSP) for Marine Litter defined by the OSPAR Commission emphasizes this by defining four themes of actions: „A. the reduction of litter from sea-based sources and B. the reduction of litter from land-based sources, C. the removal of existing litter from the marine environment and D. education and outreach on the topic of marine litter” (OSPAR Commission, 2014).

In terms of the reduction of litter, the best option would be to change the materials used for production and to limit the use of plastic in products. In research there has to be a stronger emphasis on materials which are not harmful in any way, also after degradation, in case they somehow enter into the ecosystem or the food chain. Furthermore, product design needs to be changed and focused on a longer usability of products. This will reduce waste in general and reduces the risk of entering the oceans. Implementing these long-term goals will be difficult. Therefore, other instruments described in chapter 4.2.5 should be implemented as well. Especially the extended producer responsibility (EPR) (OECD, n.d.) in combination with monitoring and sanctions from the legislator could play an important role in reaching these goals.
As collection is easy to implement, collection of marine plastic debris can help to make people more aware of the problem and thus trigger a rise in calls for more measures to address the problem. Collections at coastal regions can help to improve aesthetic and biodiversity problems. Cleaning activities at beaches with tourism are the most important as most of the litter on beaches is not washed ashore but caused by beach users themselves (Kordella et al., 2013) (see chapter 4.2.1). Additionally, the cleanliness of beaches influences incomes of local businesses from recreational activity. Chapter 4.2 may help in finding new solutions for the management of marine plastic and in finding evaluation tools. If done efficiently, and with the help of simulations, off-shore collection can complement the set of instruments for tackling marine plastic debris and can offer a monitoring tool for evaluations in order to prevent free-riding.

4.3 Recycling of marine plastic debris

This chapter focuses on the possibilities of an on-board recycling for marine plastic after collection with a net. Chapters 4.3.1-4.3.3 review the possibilities of plastic recycling and reflect their possible usage for marine plastic debris recycling.

4.3.1 Mechanical recycling

Mechanical recycling uses re-melting and re-processing of plastic waste in order to produce new plastic products. Generally, mechanical recycling of plastics is possible. Mixing different kinds of plastic influences product quality negatively, because of repulsion effects and because its properties change dramatically (Bandrup, 1995; Vasudeo et al., 2016). Mechanical recycling only works within one kind of plastic because of this limited compatibility, and is mostly limited to thermoplasts (Vasudeo et al., 2016, p. 42). Mechanical recycling of marine plastic debris is not possible because different thermoplasts and thermosets are mixed (Morét-Ferguson et al., 2010) and their separation is impossible, since most of the plastics are already partly decomposed, and the composition is difficult to identify (Hidalgo-Ruz et al., 2012; Löder and Gerdts, 2015).

4.3.2 Feedstock recycling

Feedstock recycling is based on the decomposition of polymers. The process of production is reversed, meaning that the end products of feedstock recycling are monomeres or a “feedstock”. The feedstock can be used to make raw materials like monomers or other petroleum products like waxes, paraffin or fuel. Fractions of these recycling processes are gaseous, solid and liquid and its composition and proportion depends on the specific method, reactor geometry and the materials (plastics) used (López et al., 2010).

The possibility of using recycling products made of marine plastic debris as feedstock still has to be tested. Currently, there is no literature about feedstock recycling of marine plastic debris, only on mixed plastic wastes.

There are different ways of feedstock recycling, using heat, chemical agents and catalysts (Vasudeo et al., 2016). **Thermal degradation** can be realized by various processes. In this work it is focused on **high temperature pyrolysis** (750-950°C and absence of oxygen in the atmosphere), **hydrogenation**, also called hydrocracking (hydrogen atmosphere) (Goodship, 2007), and gasification. The Veba-Combi-Cracking-process (**VCC-process**) is an established hydrocracking method proved also for large-scale application and used to produce oil (Martens, 2011, p. 192). One drawback of hydrogenation is the high cost of hydrogen and the high pressure (200-250 bar) needed for the process (Martens, 2011; Vasudeo et al., 2016, p. 192).

High-temperature pyrolysis is preferred over standard combustion, when the waste is broadly mixed or contaminated, because pyrolysis produces 5-20 times less gas and thus pollutants in the coke residue are concentrated. This means that the costs for cleaning effluent gas streams (scrubbing) are lower, compared to the standard combustion (Goodship, 2007, p. 116).

Low temperature pyrolysis (450-600°C) is a **depolymerisation** technique. Therefore, low temperature pyrolysis is also called cracking. The theoretical temperature needed for C-C-bonds to break is 400°C. However, in spite of this, first depolymerisation effects already appear at a temperature of 300°C because of the influence of heteroatoms, like oxygen, which are part of the chain (Bandrup, 1995, p. 17). **Solvolytic processes,** including hydrolysis (hydrocracking), methanolysis, glycolysis and ammonolysis, are also processes of depolymerisation and depend on reactions with water, alcohol or other solvents. They are intolerant of impurities, thus, additional polymers have to be extracted beforehand (Lundquist, 2000, p. 58). This research field is rather new and there is not enough data for designing reactors. There are some major advantages of these processes, like the possibility to separate plastic types, as different plastics are solved by different solvents (Wong et al., 2015, p. 1172). However, addition polymeres make depolymerisation into original monomeres by reverse synthesis reaction difficult (Panda et al., 2010).

Thermal conversion can be categorized by their air requirements in pyrolysis, hydrogenation and gasification. The process of **pyrolysis** takes place without any oxygen (oxygen depleted environment), **hydrogenation** uses a hydrogen or carbon monoxide atmosphere and in **gasification**, the partial combustion occurs within limited air, oxygen, steam or carbon dioxide (Goodship, 2007, p. 115; Martens, 2011, p. 194). Gasification is explained in the next chapter (4.3.3 Energy recovery).

In **catalytic cracking**, catalysts are used to lower the reaction temperature and time, and to promote plastic degradation (Panda et al., 2010; Vasudeo et al., 2016). Most of the studies use batch or fixed bed reactors even though other reactor types may be more suitable (Vasudeo et al., 2016).
There are different methods of cracking. For example, Walendziewski (2002) describes a batch-process. In this process, polyethylene (PE), polystyrene (PS) und polypropylene (PP) were cracked under atmospheric pressure. Temperatures were 350-380°C at first and then raised to over 400°C. Compared to the process in an autoclave under hydrogen atmosphere (pressure of approx. 3-5 MPa, 380-440°C) the gaseous fraction is smaller (Walendziewski, 2002).

The use of marine plastic debris for feedstock recycling is possible, but there will be problems to reach a constant product quality in order to produce resources for the chemical industry. One of the major **problems** which may emerge is the **chlorine** which is contained in polyvinyl chloride (PVC) and NaCl (salt) as well as other halogens (Bandrup, 1995, p. 416). Especially for high-valued petrochemical products, a low metal-, chlorine- and nitrogen-contamination is essential (Bandrup, 1995, p. 430). For fuel production (see 4.3.3 Energy recovery), a low chlorine concentration is important too because chlorine lowers the viability of liquid fuel usage and causes corrosion (Wong et al., 2015). There are different methods for **dechlorination**, such as catalytic pyrolysis, pyrolysis with added adsorbents, or a stepwise pyrolysis (López et al., 2011). Catalytic pyrolysis uses special catalysts which inhibit the formation of HCl. When added, adsorbents will trap the HCl physically and/or chemically in the solid residuals (López et al., 2011). In a stepwise pyrolysis, a lower temperature (300°C) is used at first where the HCl can be separated as gas. The gas in the first step contains most of the chlorine, in the third run the chlorine content of the gas phase is reduced to 0.0044% (Bockhorn et al., 1999; López et al., 2011).

Analyses of the **composition of marine microplastics** show that they mainly (48%) consist of polyethylene (PE) and polypropylene (PP). Both of them increase in percentage as the distance from the coast becomes greater (Enders et al., 2015, p. 75). The share of PVC in the samples of Enders et al. was 1.8%. This distribution can be explained by the density of PE and PP, which is lower than the density of seawater (Table 1) and the fact that samples were taken 3 m below the surface (Enders et al., 2015, p. 75). A low PVC concentration in the recycling material is favourable because PVC contains most of the chlorine.

Apart from chlorine, there are other substances contained in plastics like nitrogen (contained in Polyurethanen and Nylon), oxygen (PET, Polyacrylate), plasticizers, metals, stabilizers or toxic substances (Bandrup, 1995, p. 430). These substances which are not part of the traditional sources of hydrocarbons, influence the recycling process. Generally speaking, the more contaminants there are in the recycling material, the lower the quality of the feedstock recycling product is.

Marine debris will not only consist of mixed plastic waste, but will contain biomass (wood, algae etc.) as well. Wong et al. (2015, p. 1175) mentions a synergetic effect of biomass when pyrolysed with plastic.

Recent literature only is about mixed plastic waste. Samples are usually collected directly after dumping, and **degradation effects** do not have to be considered. However, when recycling marine plastic debris, plastic degradation is a major factor which influences the material properties. When produced, plastic polymers are stabilised with antioxidants and UV stabilisers, but these do not prevent aging forever. Temperature, air, light (UV-radiation Andrady, 2011) and weathering lead to natural ageing of plastics. Ageing means that the polymer-chains and other bonds are damaged (Bandrup, 1995, p. 289). Consequences of this degradation comprise the decrease in the average molecular weight, loss in bulk mechanical- and surface properties as well as changes in the spectral characteristics (Andrady, 2015, p. 60). For an overview on the different stages of aging see Table 5.

Table 5 Overview on the different aging stages of polymeres (changed from (Bandrup, 1995, p. 10)).

For the original figure see referenced paper or printed version of this thesis at the library of the University of Natural Resources and Life Sciences, Vienna.	Undamaged and pure polymere with long chains and, as a result, great firmness and toughness. When melted, it is very thick.
	Pure but aged polymere with short chains, the firmness and toughness are decreased. When melted, it is thin.
	Mixed polymers: the other polymer covers the molecule surface and no meshing occurs. Firmness and toughness are very low.

Compared to plastic debris in the seawater, stranded plastics degrade faster because of UV-radiation (photodegradation reactions) and higher temperatures (thermo-oxidation) (Andrady, 2011, 2015). Furthermore, the surface is affected by mechanical influences of sand (Corcoran et al., 2009). The opposite is true for plastic in the seawater. Therefore, it is assumed that degradation in the ocean, especially at the bottom of the sea, is very slow because of the limited radiation and cooler temperatures. Plastics at surface layers degrade faster because of the UVB-radiation, the hydrolytic properties of seawater and the oxidative properties of the atmosphere (Moore, 2008). Additionally, there is another cause of deconstruction of polymers in the ocean, called microbial **biodegradation** (Andrady, 2015; Ryan, 2015). A shift in the use of materials from traditional plastics to compostable polymers can be seen as another path to solve the problems of marine plastic. Some of these plastics are made of renewable raw material (Jovanović et al., 2013), producing this raw material brings other problems. The soil for food production is the same as for these renewable materials and the area of fertile land is limited. There are also biodegradable polymers from petrochemical sources. Most of the testing whether a polymer is degradable or not is done in composting conditions with temperatures about 60 °C (Rudnik, 2008). These conditions are totally different than in the ocean and degradation of degradable plastics. Tests with the starch based bioplastic Mater-Bi showed that surface erosion was only 1.5% of their initial values of weight after three months of exposure to the sea, compared to 68% of the same material buried in compost (Accinelli et al., 2012). This is caused by the lower temperatures, radiation and the limited amount of bacteria and fungi capable of degrading the plastic in the sea.

Some of the stranded marine plastic debris may re-enter the ocean or be buried under the sand and re-exposed to the air by wind, waves, rain or melt water (Eriksson et al., 2013). For this reason, all of these degradation effects may apply to the collected marine debris recycling material.

Floating plastics with a density lower than sea water may sink because of **biofouling**. Algae and other taxa which populate the surface of polymers increase their density and this results in buoyancy loss (Fazey and Ryan, 2016).

Martens (2011, p. 188) argues that feedstock recycling is only **profitable** with large quantities of plastic waste. Feedstock recycling of filtered marine plastic debris on a ship means dealing with smaller volumes (see 5.2 Results) as well as mixed plastics, which are partly degraded. Gaining a product with sufficient quality for further use may not be impossible, but will definitely not be economically efficient. In the oceans, there are expected to be about 7 000 - 35 000 tons of plastic (Cózar et al., 2014a), but in comparison to professional recycling, the amounts is rather low. Ecoplast in Styria (Austria) for example deals with 28 000 tons of plastic per year (Ecoplast Kunststoff-Recycling GmbH, 2013).

Nontheless, processes like pyrolysis and gasification can be used for energy recovery.

4.3.3 Energy recovery

„Energy recovery can be defined as incineration to recover inherent energy “(Goodship 2007, 118). Energy recovery may be the best way to recycle marine plastic debris for more than one reason. Firstly, the calorific value of plastic (e.g. polyethylene 43 MJ/kg) is similar to fuel oil (43 MJ/kg) or gasoline (46 MJ/kg) (Panda et al., 2010). Secondly, there is also the possibility of pyrolysis, hydrogenation or gasification for fuel production. In this case, the requirements for product quality are lower. Thirdly, when plastic is collected at sea, energy recovery can be used in order to reduce the volumes of collected debris, as well as a way to recover energy for collection itself. Incineration of plastic or fuel made out of plastic can be used to produce heat and electricity.
Monetary costs of debris collection vary from 100 USD/t (volunteer collection on coasts) to 20 000 USD/t (collection from the bottom) (McIlgorm et al., 2011). Recycling the collected debris is the only possibility to regain some of the expenditures of collection. Mechanical recycling of marine plastic debris is not possible. Methods of feedstock recycling can be used for collected marine plastic debris, but is not economically efficient (see chapter 4.3.2 Feedstock recycling). Thus, the costs of this recycling method cannot be justified. Energy recovery is the best option for recycling in this case.

The drawback of incineration is that harmful emissions could pollute the water and the air. Therefore, the legal requirements need to be met and emissions have to be filtered (Tabasová et al., 2012).

The London Convention and Protocol prohibits the incineration of wastes or other matter at sea. “Incineration at sea” is defined as „combustion on board a vessel, platform or other man-made structure at sea of wastes or other matter for the purpose of their deliberate disposal by thermal destruction” (London Protocol, 2006). But this prohibition “does not include the incineration of wastes or other matter on board a vessel, platform, or other man-made structure at sea if such wastes or other matter were generated during the normal operation of that vessel, platform or other man-made structure at sea” (London Protocol, 2006).

Material composition, degradation and biofouling, as described in chapter 4.3.2 (Feedstock recycling) will influence the product quality and the recycling process.

There are different methods of producing fuel from plastic waste. **Pyrolysis** uses different temperatures of various hydrocarbons in order to produce a specific type of fuel. A particular temperature and catalyst can be used to influence the products properties (Kunwar et al., 2016, p. 422f). The pyrolysis oil has properties equivalent to diesel; therefore, waste plastic pyrolysis oil can be used as an alternate fuel for diesel engine without any modifications (Devaraj et al., 2015) and its gross calorific value (*GCV*) is also comparable to conventional fossil liquid and gaseous fuels (López et al., 2010). Residues from pyrolysis can be used as well. The organic fraction of residues can be used for energy recovery and the inorganic fraction may be recovered for recycling processes (López et al., 2010). Due to high viscosity and low thermal conductivity of plastics energy and mass transfer are restricted (Kunwar et al., 2016).

In **hydrogenation**, the products are highly saturated and olefins in the liquid fraction are avoided, which leads to better usability for fuel usage. Furthermore, the removal of the heteroatoms Cl, N and S is promoted (Aguado Alonso and Serrano, 1999, p. 161; Vasudeo et al., 2016). There are not enough studies in order to decide the usability of hydrogenation for marine plastic debris energy recovery.

The **gasification** process can be allothermal or autothermal. Allothermal means, that the heat comes from outside the reactor, when the heat is generated by partial oxidation or partial combustion, it is autothermal (oxidative) (Brattsev et al., 2011; Milhé et al., 2013). Gasification was developed for use with coal or oil, but it can also be used with plastic to produce synthetic gas. Temperature (800 – 1 600°C) and air composition depend on the type of fuel (Goodship, 2007). The process pressure amount to 1-150 bar.

The gasification agent is oxygen, carbon dioxide, water steam or in some cases also hydrogen.

Partial oxidation with air generates a syngas which is diluted with up to 60% atmospheric nitrogen. The gas has a calorific value between 4 - 7 MJ/Nm^3. This syngas can only be used in special new-generation gas turbines or gas engines which are built to burn low heating value syngas (Arena, 2012). When partial oxidation is done with pure oxygen, there is almost no nitrogen in the syngas and its calorific value is higher (up to10 - 15 MJ/Nm^3). Another method to obtain nitrogen-free syngas is the steam gasification. The heating value of the steam gasification product is higher (15 - 20 MJ/Nm^3), but external energy must be used for endothermic gasification reactions (Arena, 2012).

After quenching and gas purification, the gas mixture can be used in an engine or for heat production, as well as for the production of methanol, ammonia and other types of alcohol (Lundquist, 2000; Martens, 2011, p. 194; Vasudeo et al., 2016, p. 59). A major advantage is that the product is only gas and no separation plant is needed. This fact favours the production of fuel gas (Goodship, 2007, p. 117f). Furthermore, the different polymers do not need to be separated (Vasudeo et al., 2016).

Gasification can be achieved by using different reactor types – for example the fixed bed reactor (Martens, 2011, p. 195) and the blast furnance - and different methods like the thermoselect-method or the two-stage pyrolysis-gasification (Gebauer and Stannard, 1995).

The two-stage pyroysis-gasification is a proven method for gasifying mixed plastics (Wu and Williams, 2010, p. 3022). The **two-stage pyroysis-gasification** process (see Figure 8) starts with synthesized gas which has been produced at 500°C in a pyrolysis process. The described process is realized in bench-scale but can be scaled up for larger reactors. Water is introduced into the first reactor by a syringe pump. Then the steam gasification follows, in which the gas is further heated up to 800 or 580°C in a second reactor, where a Ni–Mg–Al catalyst and steam are present. At last, the gas is passed through a condenser and is collected. The introduction of steam into the non-catalytic pyrolysis–gasification has shown to increase the gas yield and reduce the solid fraction (Wu and Williams, 2010, p. 3024). For other methods of two-stage pyrolisis-gasification see (Wong et al., 2015).

For the original figure see referenced paper or printed version of this thesis at the library of the University of Natural Resources and Life Sciences, Vienna.

Figure 8 Schematic diagram of a two-stage Pyrolysis-gasification system used in (Wu and Williams, 2009)

Gasification in a **fixed bed reactor** is realised at 1 200°C and 25 bar. Contamination should be avoided and the material has to be very homogeneous. Temperature and pressure influence the proportions of CO, H_2 und CH_4 (Martens, 2011, p. 195).

The first experiment with heterogeneous marine plastic debris, including also some stones showed that it is well fluidizable in a cold fluidized bed reactor (Schröfl, 2016). Figure 9 shows a flow sheet of the pilot scale plant which is used for fuel gas production by Arena and Di Gregorio (2014). As one example of gasification for energy recovery, and because this paper serves as the basis for further calculations (chapter 5 Calculation of a marine plastic debris collection and gasification), the following paragraph summarizes the process Arena and Di Gregorio applied.

For the gasification in a **fluidized bed** reactor, a bed of olivine is used (also possible would be for example sand). The blast agent (air) is heated up in tree steps, first by an electric heater (150°C), then it is transferred to a mixing point by a stream of steam of 150°C and finally, it is heated up to the desired inlet temperature (200°C). The blast material is introduced from the bottom of the reactor, whereas the feedstock and nitrogen, used as transport gas, are fed from above the bed. Preheated air is used as blast agent. The reactor is further heated up to about 700°C by three external electrical furnaces. After gasification the syngas is cleaned using a cyclone to abate fine particles and a wet scrubber to remove tar, residual dust, acid gases and ammonia and finally a flare is used.

The fluidized bed reactor is preferably used in a continuous process. This has many advantages, for example the process does not have to be restarted that often and it is less labour-intensive (Wong et al., 2015). The temperature can be easily influenced, heat transfer from reactor to the polymere is excellent, reactions are constant and the process is well established (Martens, 2011, p. 194). The constant temperature of the reactor improves the homogeneity of the end product (Wong et al., 2015, p. 1170). Facing varying supply of recycling material and relatively small volumes (see chapter 5.2 Results) a batch process will be better suited for an offshore recycling process. For **other reactor types** like the conical spouted bed reactor, screw kiln reactor, batch and semi-batch reactor for fuel production, see Wong et al. (2015).

For the original figure see referenced paper or printed version of this thesis at the library of the University of Natural Resources and Life Sciences, Vienna.

Figure 9 Scheme of a bubbling fluidized bed gasifier, with some typical operating parameters used in Arena and Di Gregorio (2014).

When syngas is used in a gas engine in order to sustain the collection ships drive, the cleaning of syngas has to be considered. The main disadvantage of this usage of syngas is that the engine components are exposed to the combustion products. Therefore, tar, dust, alkalies and heavy metals have to be limited and the maintenance intervals of the gas engine are short and thus expensive (Arena, 2012).

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Figure 10 Two different configurations of gasification: power gasifier and heat gasifier (Arena et al., 2011)

There are two different techniques for cleaning syngas. Using heat gasifier configurations, the syngas is burned first and the exhaust gases are cleaned afterwards. However, this thesis focuses on the usage of producer gas for a gas engine of a ship in order to reduce energy consumption for the collection of marine plastic debris by applying **power gasifier** configurations. In the power gasifier, the producer gas is cleaned first and then burned (see Figure 10) (Arena et al., 2011).

Similar to the heat gasifier, marine plastic waste could be **combusted** normally. There, the exhaust fumes have to be filtered as well before they are emitted into the air and combustion heat can be used. With the help of a steam turbine electricity could be generated. However, there are difficulties in the lower power range and high temperatures and heat losses may be problematic on a ship.

Thus, this kind of energy recovery is not considered further in this work.

The use of alternative energy can be beneficial in the case of a mobile offshore collection and recycling facility. The necessary energy for the ships engine and other equipment could be provided by using solar or wind power. Since this is not the focus of this master thesis, alternative energy is not discussed.

5 Calculation of a marine plastic debris collection and gasification

The following calculation of a collection and gasification of marine plastic gives the massflow and product yield as well as the fuel savings if the gasification product is used as fuel for the collection ship. Gasification is chosen because of its advantages regarding material quality (different polymers do not need to be separated (Vasudeo et al., 2016)) and because no separation plant is needed. Since no references to an actual gasification of marine plastic debris could be found, calculations are based on data from mixed plastic waste gasification.

5.1 Method

Literature about microplastic in marine environment is increasing, there are still huge differences in sampling techniques, and studies that give a plastic density in g/km^2 are very rare. Based on the data from Table 6 and the results from Cózar et al. (2014b) and Cózar et al. (2015, p. 6) shown in Figure 11 and Figure 12, three different scenarios are assumed. The scenario with the highest *plastic density p* is called “maximum yield” (p = 5 000 g/km^2), then there is also a “realistic yield” (p = 3 000 g/km^2) and a “minimum yield” scenario (p = 300 g/km^2).

Table 6 Densities of marine plastic litter in different regions used for reference

mean mass *p*	sampling area	mesh size	reference
5 114 g/km^2 (64 - 30 169 g/km^2)	Surface of North Pacific central gyre, surface	333 micron net	(C. J. Moore et al., 2001)
281 – 639 g/km^2	Subtropical ocean gyres	-	(Cózar et al., 2015, p. 5)
423 g/km^2	Mediterranean surface waters	0.2 mm	(Cózar et al., 2015, p. 5)
3 000 g/km^3	Southern California shore	333 micron net	(Lattin et al., 2004)
2 000 g/km^3	Southern California shore	333 micron net	(Moore et al., 2002)
60 000 – 400 000 g/km^2	Mediterranean 1387-3000 m depth	20 mm/ 40 mm	(Pham et al., 2014)
1 - 10 000 g/km^2	Global model	0.33 mm	(Eriksen et al., 2014)

Extension of Table 6

mean mass *p*	sampling area	mesh size	reference
300 – 3 500 g/km^2	North Pacific Garbage Patch	150 µm	(Wong et al., 1974, p. 30)
46 - 1 210 g/km^2	North Pacific Garbage Patch	-	(Liubartseva et al., 2016)
0 – 153 000 g/km^2 Mean: 3 600 g/km^2	Western North Pacific Ocean	330 µm	(Yamashita and Tanimura, 2007)
70.96 g/km^2(mean)	North Pacific Garbage Patch	-	(Liubartseva et al., 2016)
290 g/km^2	Western Sargasso Sea	-	(Carpenter and Smith, 1972)
16.7 g/km^2	Northern South China Sea	<2.5 <=10 cm	(Zhou et al., 2011)

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Figure 11 Plastic density (g/km^2) of three different accumulation zones: blue: non-accumulation zone, green: outer accumulation zone, red: inner accumulation zone (box boundaries 25th and 75th percentiles, mean (black line in the box) and whiskers (90th and 10th percentiles)) (Cózar et al., 2014b)

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Figure 12 Surface plastic density (g/km^2) A) Mediterranean Sea (blue) and the global ocean (red) “Frequency distribution of the measures of plastic concentrations in the Mediterranean Sea (n = 72) and in the global ocean (n = 1760). B) of the Mediterranean Sea and for the inner accumulation zone of the five subtropical gyres including the mean (black dots) and the median (white dots)” (Cózar et al., 2015, p. 6).

Results from Smailys et al. (2016) are used for the calculation of the emissions from the ship during collection (which is assumed to take place 356 days per year and 24 hours a day) the size of the net and the ships speed are also taken from this study. Regarding the latter, only speeds from 0.6 to 2 m/s (0.6/ 1/ 1.4/ 1.8/ 2 m/s) (1 kn = (1852/3600) m s^{-1} (Generalic, 2017)) are used because results were extrapolated to 0.2 m/s and are therefore not included in these calculations. Due to the lack of literature dealing with the collection or recycling of marine plastic debris, assumptions (see Table 7) had to be made.

Table 7 Assumptions made for the calculation of marine plastic gasification

assumptions		**unit**	**reference**
period	365 24	days/year h/day	
recycling method	air gasification of marine plastic debris		
$LCV_{marinediesel}$	42.5	MJ/kg	(Deniz and Zincir, 2016; Gohary and Seddiek, 2013; Kołwzan and Narewski, 2012)
$LCV_{plasticgas}$	6590 =6590	kJ/kg kJ/Nm^3	(Arena and Di Gregorio, 2014)
maximum yield density $\mathbf{p}_{max}$ of marine plastic	0.005	g/m^2	
realistic yield density $\mathbf{p}_{real}$ of marine plastic	0.003	g/m^2	
minimum yield density $\mathbf{p}_{min}$ of marine plastic	0.0003	g/m^2	
Nets capacity (Cap_{net}) for 5 diffentent speeds	3000, 9100, 15100, 21200, 27200, 30200	*m^2/h*	(Smailys et al., 2016)
Emissions from collection (e_{NOx}^{net} e_{SO2}^{net}, e_{CO}^{net}, e_{CO2}^{net}) for 5 different speeds	see Smailys et al., 2016	*kg/m^2*	(Smailys et al., 2016)
Speed *v* of the ship during collection	0.6; 1; 1.4; 1.8; 2	*m/s*	(Smailys et al., 2016)
Air/fuel	3.18	*$kg_{air}/kg_{plastic}$*	(Arena and Di Gregorio, 2014)
gas production rate *r*	4	$\frac{kg_{producer\ gas}}{kg_{plastic}}$	(Arena and Di Gregorio, 2014)

Calculation of the yearly plastic yield

First, the yearly plastic yield y $[kg]$ is calculated:

$$y = \frac{(Cap_{net} * \text{ p}) * 24 * 365}{1000}$$

$$[kg] \ = \frac{([m^2/h] * [g/m^2]) * h * days}{1000}$$

This calculation is made for all five speeds and for all three plastic densities are calculated (maximum yield p_{max}, realistic yield p_{real} and minimum yield p_{min}).

Calculation of the yearly emissions from plastic collection

The yearly emissions from the collection by ship which are used in the measurements by Smailys et al. (2016) are calculated for the three plastic densities and the different speeds using the following formula:

$$e_j^{net,y} \ = \ e_j^{net} * Cap_{net} * 365 * 24$$

$$[kg/year] = [kg/m^2] * [m^2/h] * days * hours$$

The emissions ($e_j^{net,y}$) were calculated for all pollutants *j* (e_{NOx}^{net}, e_{SO2}^{net}, e_{CO}^{net}, e_{CO2}^{net}).

Calculation of the yearly fuel consumption

Smailys et al. (2016) also measured the fuel consumption g_f^{net} $[kg/m^2]$ during the collection of plastic debris hence the fuel consumption for the whole period fc $[kg/m^2]$ can be calculated:

$$fc \ = g_f^{net} * Cap_{net} \ * 365 * 24$$

$$[kg/m^2] * [m^2/h] * days * h$$

This calculation is made for all five speeds.

Calculation of the power needed for marine plastic debris collection

With the estimated lower calorific value LCV_{diesel} $\left[\frac{MJ}{kg}\right]$ of the marine diesel which was used, the power needed for plastic collection P_{diesel} $[W]$ can be calculated for the period:

$$P_{diesel} = \frac{(fc \ * LCV_{diesel}) * 10^6}{365 * 24 * 3600}$$

$$[W] = \frac{[kg_{fuel}/year] * [MJ/kg]}{days * hours * seconds}$$

This calculation is made for all five speeds and for all three plastic concentrations (maximum yield, realistic yield and minimum yield).

Calculation of the power received from plastic gasification

Assuming the gas production rate r is 4 $[kg_{producer\ gas}/kg_{MPW}]$ and further assuming that all collected debris can be converted into gas with a lower calorific value $LCV_{plasticgas}$ of 6.59 MJ/Nm^3 (Arena and Di Gregorio, 2014) and assuming that this equals 6.59 MJ/kg, the following calculation of the power received from air gasification of marine plastic debris can be made:

$$P_{plastic} = \frac{(y * r * LCV_{plasticgas}) * 10^3}{365 * 24 * 3600}$$

$$[W] = \frac{\left(\left[\frac{kg_{plastic}}{year}\right] * \left[\frac{kg_{producer\ gas}}{kg_{plastic}}\right] * \left[\frac{kJ}{kg}\right]\right) * 10^3}{days * hours * seconds}$$

The $LCV_{plasticgas}$ and r are assumed to be the same as for MPW (mixed plastic waste) as measured by (Arena and Di Gregorio, 2014). This calculation is made for all five speeds.

Calculation of the relative power savings $P_{plastic_{rel}}$ if gasification gas is used as the ships fuel

Relative power savings can be calculated:

$$P_{plastic_{rel}} = \frac{P_{plastic}}{P_{diesel}} * \ 100$$

$$[\%] = \frac{[W]}{[W]} * 100$$

The plastic gasification product is assumed to be used by the ship´s engine. $P_{plastic_{rel}}$ is the share of P_{diesel} that can be substituted by the gasification product and is therefore called a power saving. $P_{plastic_{rel}}$ is the relative amount of marine diesel used by the engine that can be substituted by plastic gas produced on board from the collected plastic. This calculation is made for all five speeds and for all three plastic densities (maximum yield, realistic yield and minimum yield).

Calculation of the absolute power needed for collection if power savings though gasification are considered

The new power needed for plastic collection at sea is calculated as follows:

$$P_{diesel_{new}} = P_{diesel} - \ P_{plastic}$$

$$[W] = [W] - \ [W]$$

This approach assumes that all the power received from plastic gasification can fully substitute the same amount of power needed for the ship. Therefore, this reduced power demand is called $P_{diesel_{new}}$. In other words, it is suggested that the gasification product can substitute part of the fuel. This calculation is made for all five speeds and for all three plastic densities (maximum yield, realistic yield and minimum yield).

5.2 Results

Under the restrictions described in Table 7 (Assumptions made for the calculation of marine plastic gasification), the yearly yield of marine plastic collection $y\ [kg]$ is estimated between 24 and 1 323 kg (Table 8 and Figure 13) depending on the velocity of the collection net and the concentration of plastic in the sea. In order to move the ship in the collection area at the speed *v,* fuel (Table 9) is burned.

Table 8 The yearly plastic yield y from marine plastic collection

v	**maximum yield y^{max}**	**realistic yield y^{real}**	**minimum yield y^{min}**
[m/s]	kg/year	kg/year	kg/year
0.6	398.58	239.15	23.91
1	661.38	396.83	39.68
1.4	928.56	557.14	55.71
1.8	1 191.36	714.82	71.48
2	1 322.76	793.66	79.37

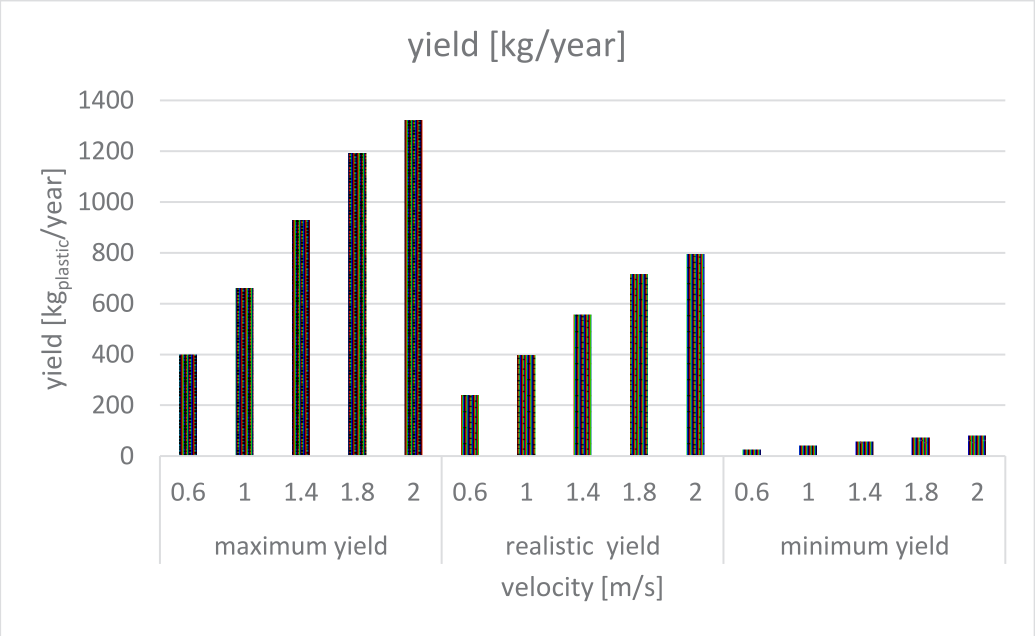

Figure 13 The yearly plastic yield y from marine plastic collection at different concentrations of plastic at the sea surface.

Table 9 The yearly fuel consumption fc of the ship

v [m/s]	fuel [kg/year]
0.6	1 761.72
1	5 595.27
1.4	11 569.86
1.8	18 966.45
2	22 857.29

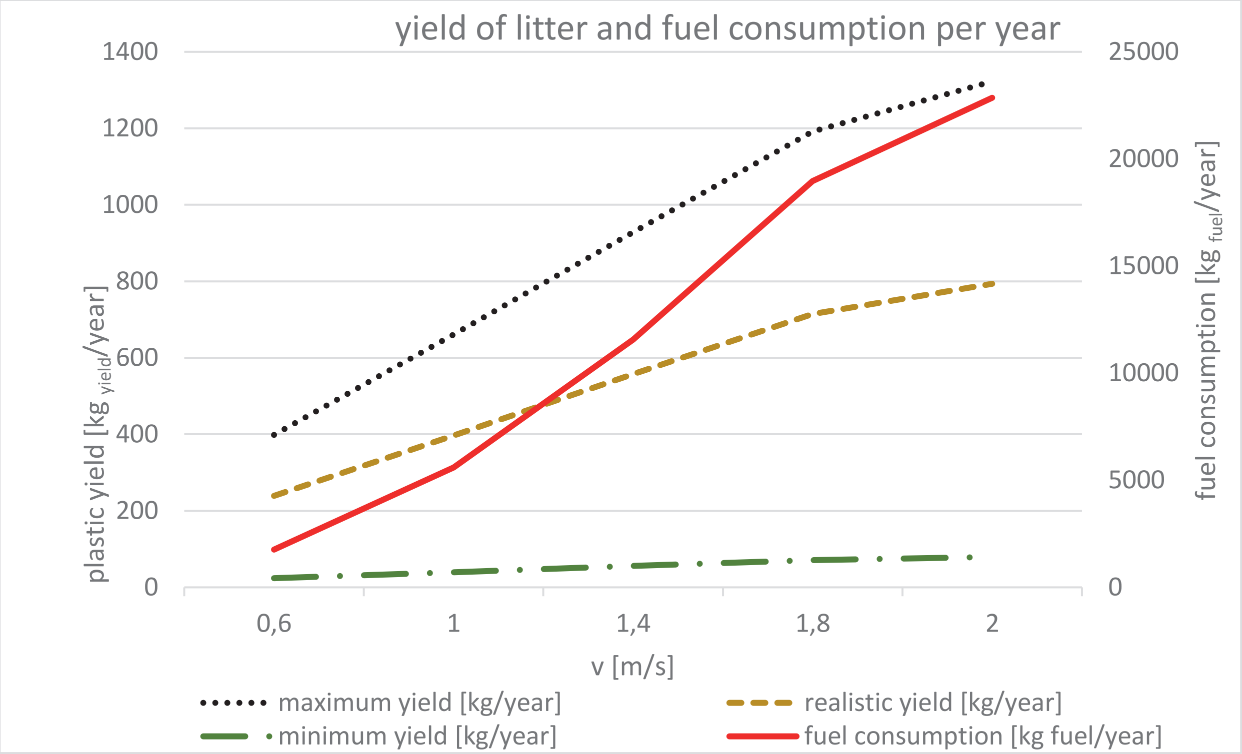

Figure 14 Yield of marine plastic collected in one year and fuel consumption for this collection

Both, the collected amount of plastic and the fuel consumption (Figure 14) rise with the increase of the collection velocity *v*. Furthermore, the scenario with the highest plastic concentration (maximum yield) has the most dramatic increase and the one with the lowest density (minimum yield) has the smallest increase with velocity *v*.

Table 10 Yearly CO, NOx, SO₂ and CO₂ emissions $e_j^{net,y}$ from the collection ship

yearly emissions				
v	$e_{CO}^{net,y}$	$e_{NOx}^{net,y}$	$e_{SO2}^{net,y}$	$e_{CO2}^{net,y}$
[m/s]	[kg/year]	[kg/year]	[kg/year]	[kg/year]
0.6	3.35	19.13	0.04	5 500.40
1	10.58	60.85	0.11	17 460.43
1.4	22.29	126.28	0.22	36 028.13
1.8	35.74	207.30	0.38	59 091.46
2	42.33	248.68	0.45	71 164.49

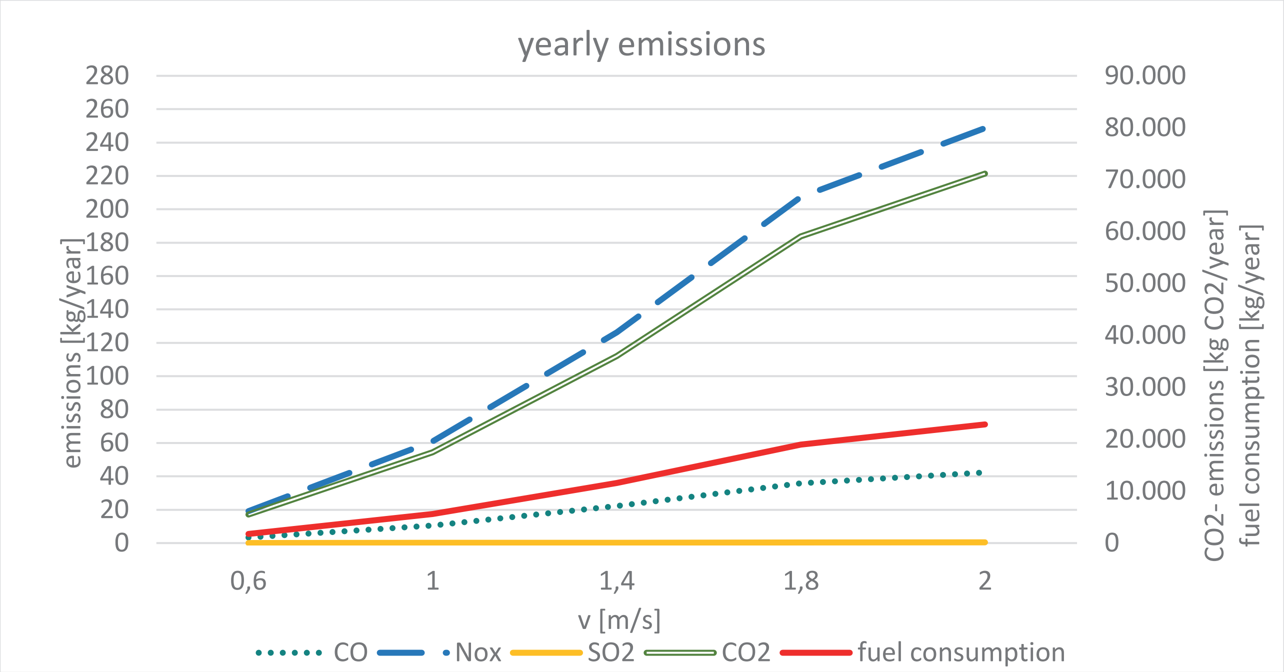

Figure 15 Yearly emissions and fuel consumption form the ship. The left axis gives all the emissions except for CO_2. The right axis gives the CO_2-emissions and the fuel consumption.

The ship´s emissions are strongly dependent on its speed v (Yau et al., 2012) (see Figure 15). As expected, the emissions from the ship in this model are very high, especially the CO_2 emissions, and there is a massive increase with velocity. The optimal speed, in terms of a minimum of emissions, is 0.6 m/s.

Table 11 power received from plastic gasification $P_{plastic}$ and the respective relative power savings $Pplastic_{rel}$ if gasification gas is used as the ships fuel

v	$P_{plastic}$ maximum yield	$P_{plastic_{rel}}$ savings maximum yield	$P_{plastic}$ realistic yield	$P_{plastic_{re}}$ savings realistic yield	$P_{plastic}$ minimum yield	$P_{plastic_{rel}}$ savings minimum yield
[m/s]	[watt]	[%]	[watt]	[%]	[watt]	[%]
0.6	333.16	14.03	199.90	8.42	19.99	0.84
1	552.83	7.33	331.70	4.40	33.17	0.44
1.4	776.16	4.98	465.69	2.99	46.57	0.30
1.8	995.82	3.90	597.49	2.34	59.75	0.23
2	1 105.66	3.59	663.39	2.15	66.34	0.22

Converting the collected marine plastic to gas can generate fuel for the ship, which can be considered as savings (Figure 16). These savings are greater, the lower the collecting speed is (Figure 17). The power obtained by the gasification process ranges from 20 to 1 106 W (Table 11).

The data in Figure 16 and Figure 17 is summed up in Table 11.

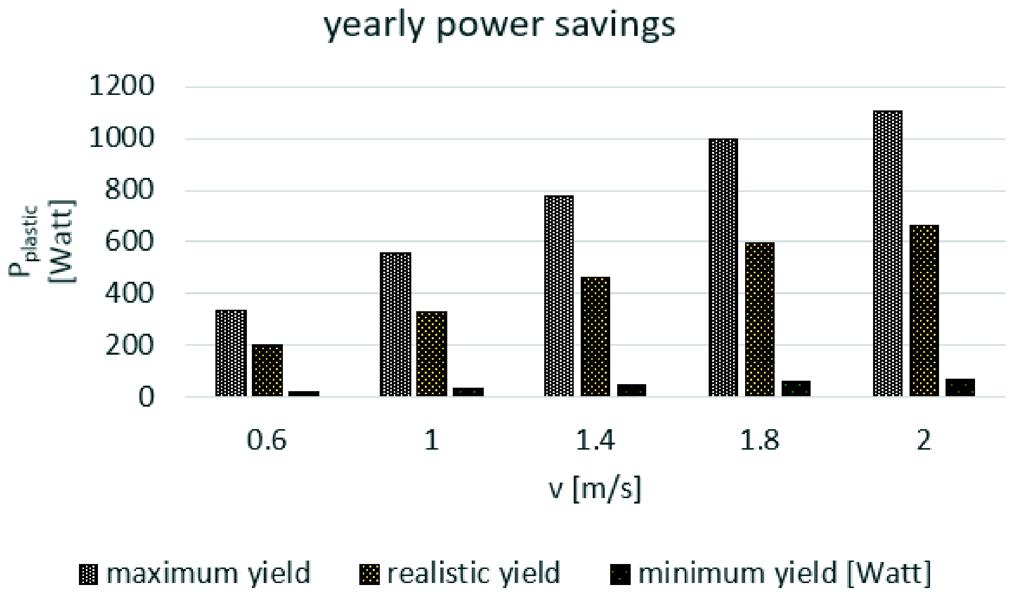

Figure 16 Yearly power savings from marine plastic gasification

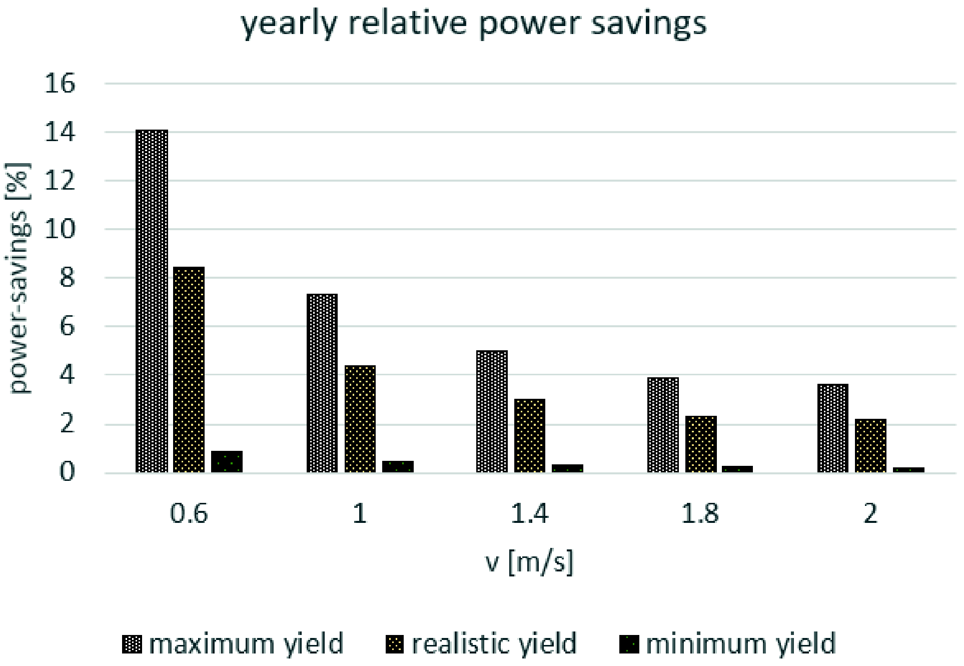

Figure 17 Yearly relative power savings

Calculations show that the most relative savings can be made at low speeds. There are huge differences in the relative as well as the absolute amount of savings at each velocity. These differences can be explained by the different estimated plastic densities at sea. Maximum yield means a high plastic debris concentration on the water surface, realistic yield a medium plastic concentration and minimum yield a lower concentration (see also Table 7 (Assumptions made for the calculation of marine plastic gasification)). The optimal velocity, regardless of the estimated concentration of plastic is 0.6 m/s.

Table 12 power needed for marine plastic debris collection with consideration ($P_{diesel_{new}}$) and without consideration (P_{diesel}) of power savings by using plastic gas for all three plastic concentrations.

v	P_{diesel}	$P_{diesel_{new}}$ with maximum yield	$P_{diesel_{new}}$ with realistic yield	$P_{diesel_{new}}$ with minimum yield
[m/s]	*[Watt]*	*[Watt]*	*[Watt]*	*[Watt]*
0.6	2 374	2 041	2 174	2 354
1	7 541	6 988	7 209	7 507
1.4	15 592	14 816	15 127	15 546
1.8	25 560	24 565	24 963	25 501
2	30 804	29 698	30 141	30 738

Considering the optimal velocity of 0.6 m/s regarding both, the emissions and the relative power savings, the vessel's engine has to be optimized at 2.4 kW (Table 12). The expected amount of plastic removed from the ocean at this speed is approximately 24 to 400 kg/year, bearing in mind the assumptions made for these calculations (see Table 7). Figure 18 shows the comparison of total power consumed by the collection ship and the recovered power from the recycling process of collected marine plastic debris at the optimal velocity exemplarily. As seen in Figure 17, the power from gasification relative to the power used for the collection is most at 0.6 m/s.

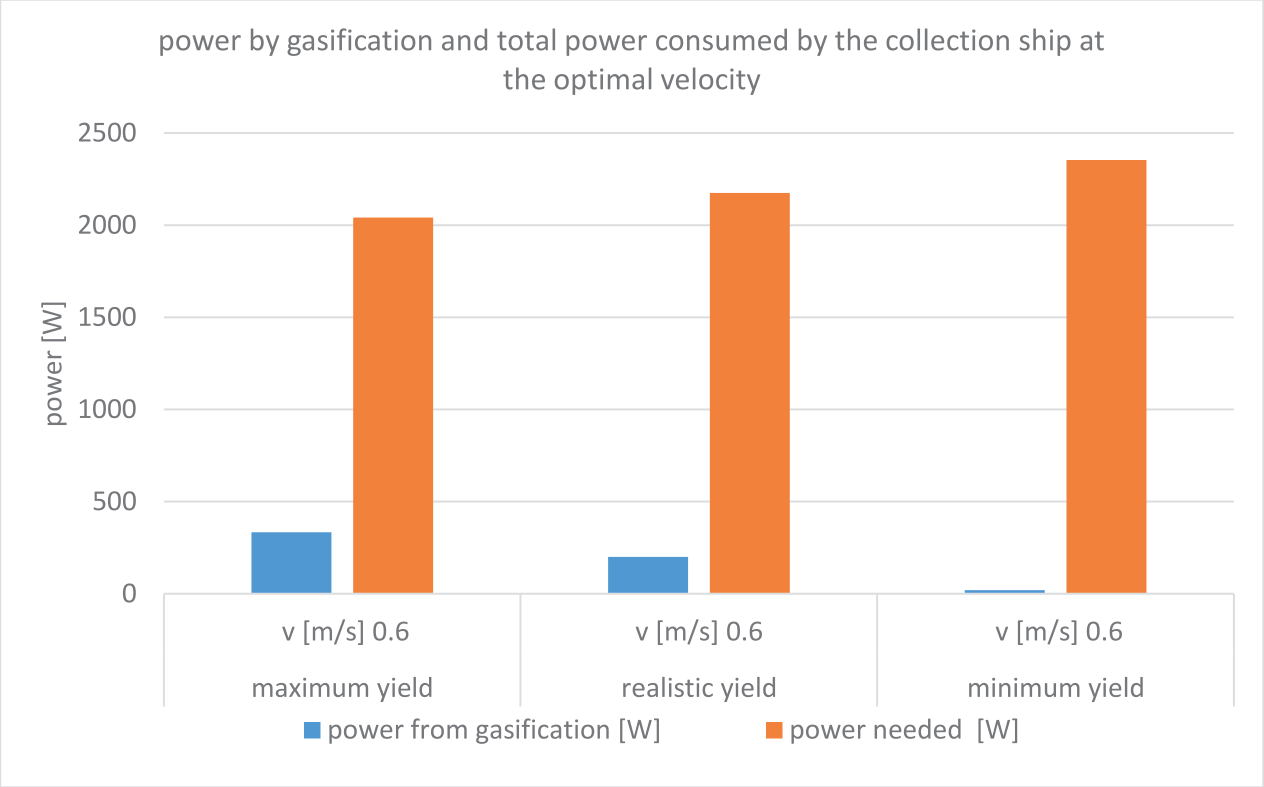

Figure 18 The power that is available by using gasification in comparison to the total power consumed by collection ship at the optimal collection speed, assuming three different plastic concentrations at the sea surface.

6 Discussion

Off-shore recycling on board of the collection ship is focused on in this work because accumulation zones are in the middle of the oceans (see Figure 3) and transportation to the closest recycling facility was expected to be more expensive and would generate more emissions than recycling on board. The advantage of a recycling ship is that it is flexible and collection in remote areas is also possible; however, it should only be used for collections at hot spots, which can be calculated by scientists´ simulation models basing on samples. One example for high plastic debris concentrations is the Po Delta in the Mediterranean Sea with maximum fluxes of 78.5 kg/km/day in summer season (Liubartseva et al., 2016), an amount which exceeds the concentrations of this calculation.

Using energy recovery, costs of fuel can be reduced because the recycling product can be used in the ship´s engine. Taking this into account, energy recovery is the best recycling method for collected marine plastic and the calculations in this work focus on the recycling of marine plastic collected and on the direct use of the recycling product as fuel. The most efficient collection can be achieved by a very slow collection speed and an engine optimized for this velocity (Giannoutsos and Manias, 2013). Reducing the speed of the collection lowers the yield of the collection too. Emissions are linked to fuel consumption and rise with the ships velocity (Figure 14). In order to minimize emissions as well as fuel costs, a slow steaming practice is emphasized. The calculated emissions of the ship do not include emissions from the gasification process itself. Furthermore, the gasification process also requires energy, which is not included in the calculations.

Even though the recycling product is used as a fuel, the total fuel consumption has to be considered. In addition, there has to be a crew for navigation and technical support. A system with an unmanned floating recycling ship would require a lot of technology, not only for auto-navigation but also for the relocation of the collected plastic from the collection net to the recycling plant on board. The use of alternative energy (wind and sun) could reduce fuel costs as well. However, these measures are not considered in this thesis. Instead, an ideal collection effectiveness at perfect conditions is calculated. These ideal conditions allow collection at every single hour during the year, day and night. Furthermore, in the calculation the plastic concentration on the surface is constant. In reality, weather and other factors will not allow an uninterrupted collection, especially if wind and sun are used as drive. Figure 18 shows, that marine debris collection cannot be done to make profits, but because of other reasons (see chapter 4.2 Reasons to remove and recycle marine plastic debris).

The recycling technology for an on-board recycling will base on existing technologies, but there are specific conditions on a ship and the recycling facility has to be adapted to these. As described in chapter 4.3.2 Feedstock recycling, the recycling material is different from mixed plastic waste because of degradation effects and biomass in the oceans. Furthermore, the ship is moving and

the centre of gravity shifts with the movement of the waves. It has to be researched how this conditions will influence the construction of a recycling facility. A batch reactor must be used since plastic cannot be collected continuously. The batch reactor can be fed only when enough marine plastic is collected.
Whether a recycling on board of the collection ship is more efficient than a recycling on-shore, considering emissions and costs, needs to be decided when the area of collection is defined more precisely. In the case of the Po Delta (Liubartseva et al., 2016), for example, an on-board recycling will not be necessary as transport to the next recycling facility is possible at low cost.

Aiming to make the ocean plastic-free cannot be realized with a construction only covering surface debris because marine debris is found on the bottom of the sea as well (Galgani et al., 2000; Galil et al., 1995; Lee et al., 2006). At the bottom of the sea, even more debris is expected than on the surface. A plastic debris collection that reduces the amount of floating marine plastic debris measurably will reduce the concentration of plastic in the ocean thus the collection yields will drop. This, and the fact that the oceans are vast and that debris is continuously entering the ocean (Jambeck et al., 2015), indicate that a plastic-free ocean only though debris collection is not a realistic goal. To be precise, the oceans are estimated to have a volume of 1 335 000 000 km^3 (Eakins and Sharman, 2010) and the nets´ capacity used for the calculation varies between 9 100 and 30 200 m^2/h depending on the collection speed (Smailys et al., 2016).
Compared to the predicted quantities of marine plastic debris entering the oceans every year (2010: 4.8 -12.7 Mio t (Jambeck et al., 2015)) from coastal counties alone, the amount a recycling ship can collect with a 6 000 x 800 mm net for surface collection, namely 24 to 400 kg/year (see chapter 5.2), seems very low. A bigger net and recycling ship will collect more plastic and economies of scale will lower the relative costs. However, a larger ship and net will have a higher resistance power (Smailys et al., 2016). Also, rising collection speed is not recommended because of the higher emissions and lower relative fuel savings (see chapter 5.2). The total cleanup-effort by the Ocean Conservancy’s International Coastal Cleanup in 2015 comprises 8 193 200 kg collected by 791 336 people (on 40 538.8 km) (Ocean Conservancy, 2016). It has to be mentioned that these figures include all marine debris including 402 375 glass beverage bottles and 351 585 metal bottle caps (Ocean Conservancy, 2016) and therefore cannot be compared directly to the collection yields calculated.

A collection of marine plastic debris on the surface will not solve all problems connected to marine plastic debris (see 4.2.7 Summary). Especially regarding habitat protection there has to be noted that collecting floating plastic with a net will also catch non-desired floating objects like parts of plants and fishes. An automated collection system is more cost efficient because a crew for haul in the net will dramatically increase the costs. This automated system for collection still needs to be developed. If not considered in construction the net will not differentiate between fish and plastic and the collection ship itself may cause the death of marine animals.

There were different assumptions made for the calculations of the recycling process (Table 7). It is assumed that the gas production rate is 4 $kg_{gas}/kg_{plastic}$ (Arena and Di Gregorio, 2014). This rate is high. Using air gasification, most of the producer gas is N_2 (about 60% (Kim et al., 2011)), in the case of Arena and Di Gregorio there were about 66% of N_2 in the producer gas. The gas production rate can be explained by this high amount of nitrogen from the air (the gasified plastic only contained 0.2% nitrogen). Arena and Di Gregorio gasifiy with 3.18 kg_{air}/kg_{MPW} thus the "additional" 3 kg of gas per kg plastic can be explained by the used 3.18 kg of air in the gasification process. The LCV of the plastic gas is assumed to be 6.59 MJ/Nm^3, this is lower than the measured LCV of mixed plastic waste by air gasification of 14.5 MJ/Nm^3 by Kim et al (2011).
This shows that the properties of the gasification product can change significantly depending on the recycling material and method used. There is no research on recycling marine plastic debris to this day, therefore assumptions of the properties and yields of the produced gas have to be treated with care. Therefore, it is essential to use marine plastic debris for the testing of different recycling methods in order to decide for the optimal method.

The so called "garbage patches" (accumulation zones) are not actually a thick soup of plastic. Concentrations vary and most researchers do count the items per km^2, so the actual weight of the plastic has to be estimated for global models like those of Eriksen et al. (2014) and van Sebille et al. (2015). Because of that, the quantities of plastic collected by the collection ship used in the calculation where based on the measured plastic concentrations at sea in g/km^2 (see Table 6). The table summarizes all found references of marine plastic debris given in g/km^2, but only those collected at the surface could be used for the calculation. These concentrations are quite low. Despite the ocean currents and the accumulation of plastics, plastic concentrations at these hot spots are varying and collection yields per hour will fluctuate. Furthermore, the actual size of these "garbage patches" is still disputed (4.1 Definition, source and distribution of marine plastic debris). For the calculations, it was not necessary to exactly define where the collection takes place. However, for the realization of a collection project, it will be necessary to choose the best place for collection, thus more data for simulations has to be generated worldwide. In this way, areas with high plastic debris concentrations can be identified and collection can be focused on these hot spots.
The collection ship can help gathering this data. If a collection and recycling facility tracks the quantities and the location of collection, new information about the scale of the problem is acquired. The information can be provided to science (to improve simulations and collection yields) and media and may be used for the evaluation of other instruments. Monitoring is especially important for preventing negative effects on the external/social level of environmental awareness (4.2.6 Environmental awareness).

Regardless of all the possibilities of collection and recycling of marine debris, reduction of the debris entering the oceans has to be the main focus. Officials in charge need to know about recycling possibilities and a proper waste management has to be established worldwide. Furthermore, a change in the mindset of consumers and producers is necessary. They need to focus on products with a maximum shelf life which are easy to repair, reuse and recycle.

7 Conclusion and Outlook

Literature research revealed six reasons for approaching marine plastic debris collection and recycling: aesthetics, habitat and wildlife protection, human health, fishing efficiency, ease of implementation and environmental awareness. Collecting marine debris can help to tackle the problems of marine plastic debris, but cannot be the only priority in order to be effective. The overall goal in dealing with marine plastic debris should be a mixture of different instruments targeting waste generation and management on- and offshore. Instruments, like international conventions, economic instruments and command and control instruments can help to address the problem (see chapter 4.2.5). When using collection to approach marine plastic offshore, the fuel consumption can be reduced by using gasification or other methods of energy recovery. This recycling of marine plastic debris during collection reduces collection costs and material volumes. The lack of standardisation in litter collection makes it difficult to estimate the litter density in a region or worldwide. Based on three different plastic concentrations, the plastic yield of marine plastic debris collection on the water surface with a net for one year was calculated.

For the maximum concentration, a yearly yield of 1 323 kg marine plastic was calculated at the highest velocity. Assuming gasification of the yielded plastics for fuel production, fuel savings are calculated. As fuel consumption rises with velocity, relative savings are the lowest (3.6%). The highest relative fuel savings (14%) were calculated at a velocity of 0.6 m/s with maximum plastic concentrations. Considering the optimal velocity of 0.6 m/s regarding both, the emissions and the relative power savings, the vessel’s engine has to be optimized at 2.4 kW. At this velocity, the maximum plastic yield is only about 400 kg (398.58 kg) per year.

In order to reduce marine debris on hotspots in the oceans and to further collect information, a flexible offshore plastic debris collecting and recycling facility can complement existing instruments. The development of this facility should also include an information platform for scientists and the public in order to exchange data and to build environmental awareness. The project should not focus on collection alone but may also be used as monitoring tool.

Further research has to be done in several areas in order to make the development of a flexible offshore marine plastic debris collection and recycling facility possible:

- tests on different energy recovery methods and reactor types with marine plastic debris,
- including tests to specify the influence of material composition, degradation and biofouling on different energy recovery methods,
- energy supply for the recovery process,
- construction of a net with an optimal mesh size and measures,
- tests on drying methods for the recycling material on board,
- tests with plastic fuel and different engines,
- engine configuration for the optimal velocities,
- measures of the emissions from the ship and from the recycling process into the air,
- measures of the residual volume,
- establishment of a plan for further usage or safe disposal of residuals,
- evaluation of the costs of operation and maintenance,
- simulations of marine plastic debris flows,
- identification of regions with high plastic debris concentrations and optimization of the recycling ships course,
- further research on the use of alternative energy like wind and sun for collection,
- evaluation of costs and emissions of on-board recycling using plastic fuel in comparison to costs and emissions of transporting the debris to the nearest onshore recycling facilities, depending on the recycling ship´s course and areas with high concentrations in the course of one year,
- further research on the risks and consequences of marine plastic debris on ecosystems, as well as the standardisation of the methods for plastic sampling and reporting,
- further research on the composition of marine plastics
- and development of an international database (Galgani et al., 2015, p. 40).

Even though the EU mentions marine litter as an indicator for the environmental status of marine waters in its Marine Strategy Framework Directive (EU Meeresstrategie- Rahmenrichtlinie, 2008), there is still no coordination of regional or national monitoring program in Europe (Strafella et al., 2015, p. 122). Furthermore, the effects of a shift in material choice from traditional non degradable to biodegradable plastics on the problems of marine plastic debris should be researched.
Another topic of further research is the phenomena of crowd funding for environmental ventures as described in chapter 4.2.6. Do only people support those projects which already act environmentally friendly or do they compensate for their behaviour?

8 References

Accinelli, C., Saccà, M.L., Mencarelli, M., Vicari, A., 2012. Deterioration of bioplastic carrier bags in the environment and assessment of a new recycling alternative. Chemosphere 89, 136–143. doi:10.1016/j.chemosphere.2012.05.028

Aguado Alonso, J., Serrano, D.P., 1999. Feedstock Recycling of Plastic Wastes, RSC Clean Technology Monographs. Royal Society of Chemistry, Cambridge.

Albrecht, J., n.d. “Tüten töten Tiere” | Greenpeace Berlin.

Andrady, A.L., 2015. Persistence of Plastic Litter in the Oceans, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 57–72. doi:10.1007/978-3-319-16510-3_3

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605. doi:10.1016/j.marpolbul.2011.05.030

Arena, U., 2012. Process and technological aspects of municipal solid waste gasification. A review. Waste Manag., Solid Waste Gasification 32, 625–639. doi:10.1016/j.wasman.2011.09.025

Arena, U., Di Gregorio, F., 2014. Energy generation by air gasification of two industrial plastic wastes in a pilot scale fluidized bed reactor. Energy 68, 735–743. doi:10.1016/j.energy.2014.01.084

Arena, U., Di Gregorio, F., Amorese, C., Mastellone, M.L., 2011. A techno-economic comparison of fluidized bed gasification of two mixed plastic wastes. Waste Manag. 31, 1494–1504. doi:10.1016/j.wasman.2011.02.004

Ballance, A., Ryan, P.G., Turpie, J.K., others, 2000. How much is a clean beach worth? The impact of litter on beach users in the Cape Peninsula, South Africa. South Afr. J. Sci. 96, 210–230.

Bandrup, J., 1995. Die Wiederverwertung von Kunststoffen. Hanser, München Wien.

Bhattacharya, C.B., Sen, S., 2003. Consumer--Company Identification: A Framework for Understanding Consumers’ Relationships with Companies. J. Mark. 67, 76–88.

Bockhorn, H., Hentschel, J., Hornung, A., Hornung, U., 1999. Environmental engineering: Stepwise pyrolysis of plastic waste. Chem. Eng. Sci. 54, 3043–3051. doi:10.1016/S0009-2509(98)00385-6

Brattsev, A.N., Kuznetsov, V.A., Popov, V.E., Ufimtsev, A.A., 2011. Arc gasification of biomass: Example of wood residue. High Temp. 49, 244–248. doi:10.1134/S0018151X11010020

Bravo, M., Astudillo, J., Lancellotti, D., Luna-Jorquera, G., Valdivia, N., Thiel, M., 2011. Rafting on abiotic substrata: properties of floating items and their influence on community succession. Mar. Ecol. Prog. Ser. 439, 1–17. doi:10.3354/meps09344

Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., Thompson, R.C., 2013. Microplastic Moves Pollutants and Additives to Worms, Reducing Functions Linked to Health and Biodiversity. Curr. Biol. 23, 2388–2392. doi:10.1016/j.cub.2013.10.012

Buxton, L., 2016. Denmark calls for EU ban on microplastics in cosmetics [WWW Document]. Chem. Watch. URL https://chemicalwatch.com/47321/denmark-calls-for-eu-ban-on-microplastics-in-cosmetics (accessed 1.29.17).

Carpenter, E., Smith, K., 1972. Plastics on the Sargasso sea surface. Science 175, 1240–1241.

Carson, H.S., Colbert, S.L., Kaylor, M.J., McDermid, K.J., 2011. Small plastic debris changes water movement and heat transfer through beach sediments. Mar. Pollut. Bull. 62, 1708–1713. doi:10.1016/j.marpolbul.2011.05.032

CCAMLR, 2016. Home Page | CCAMLR [WWW Document]. Comm. Conserv. Antarct. Mar. Living Resour. URL https://www.ccamlr.org/en (accessed 8.7.16).

Ceglinski, P., Turton, A., n.d. THE SEABIN PROJECT - A simple solution to our oceans pollution [WWW Document]. Indiegogo. URL https://www.indiegogo.com/projects/1525725 (accessed 10.22.16).

Chen, C.-L., 2015. Regulation and Management of Marine Litter, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 395–428.

Cho, D.-O., 2011. Removing derelict fishing gear from the deep seabed of the East Sea. Mar. Policy 35, 610–614. doi:10.1016/j.marpol.2011.01.022

Cooper, D.A., Corcoran, P.L., 2010. Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. Mar. Pollut. Bull. 60, 650–654. doi:10.1016/j.marpolbul.2009.12.026

Corcoran, P.L., Biesinger, M.C., Grifi, M., 2009. Plastics and beaches: A degrading relationship. Mar. Pollut. Bull. 58, 80–84. doi:10.1016/j.marpolbul.2008.08.022

Cózar, A., Echevarria, F., Gonzalez-Gordillo, J.I., Irigoien, X., Ubeda, B., Hernandez-Leon, S., Palma, A.T., Navarro, S., Garcia-de-Lomas, J., Ruiz, A., Fernandez-de-Puelles, M.L., Duarte, C.M., 2014a. Plastic debris in the open ocean. Proc. Natl. Acad. Sci. 111, 10239–10244.

doi:10.1073/pnas.1314705111

Cózar, A., Echevarria, F., Gonzalez-Gordillo, J.I., Irigoien, X., Ubeda, B., Hernandez-Leon, S., Palma, A.T., Navarro, S., Garcia-de-Lomas, J., Ruiz, A., Fernandez-de-Puelles, M.L., Duarte, C.M., 2014b. SI Appendix for "Plastic debris in the open ocean." Proc. Natl. Acad. Sci. 111, 16. doi:10.1073/pnas.1314705111

Cózar, A., Sanz-Martín, M., Martí, E., González-Gordillo, J.I., Ubeda, B., Gálvez, J.Á., Irigoien, X., Duarte, C.M., 2015. Plastic accumulation in the Mediterranean Sea. PloS One 10, e0121762.

Davison, P., Asch, R., 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Mar. Ecol. Prog. Ser. 432, 173–180. doi:10.3354/meps09142

Deniz, C., Zincir, B., 2016. Environmental and economical assessment of alternative marine fuels. J. Clean. Prod. 113, 438–449. doi:10.1016/j.jclepro.2015.11.089

Deutsche Stiftung Meeresschutz, n.d. Plastikabfall vergiftet die Meere und tötet Meerestiere [WWW Document]. URL http://www.stiftung-meeresschutz.org/themen/verschmutzung-muell/43-plastikabfall-vergiftet-die-meere-und-toetet-meerestiere (accessed 9.7.16).

Devaraj, J., Robinson, Y., Ganapathi, P., 2015. Experimental investigation of performance, emission and combustion characteristics of waste plastic pyrolysis oil blended with diethyl ether used as fuel for diesel engine. Energy 85, 304–309. doi:10.1016/j.energy.2015.03.075

Doyle, M.J., Watson, W., Bowlin, N.M., Sheavly, S.B., 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Mar. Environ. Res. 71, 41–52. doi:10.1016/j.marenvres.2010.10.001

Eakins, B.W., Sharman, G.F., 2010. Volumes of the World's Oceans from ETOPO1.

Ecoplast Kunststoff-Recycling GmbH, 2013. Rezyklate [WWW Document]. Ecoplast. URL http://www.ecoplast.com/index.php/rezyklate/ (accessed 10.10.16).

ecover, n.d. ecover [WWW Document]. Ecover AT. URL https://www.ecover.com/at/ (accessed 10.18.16).

Edyvane, K.S., Dalgetty, A., Hone, P.W., Higham, J.S., Wace, N.M., 2004. Long-term marine litter monitoring in the remote Great Australian Bight, South Australia. Mar. Pollut. Bull. 48, 1060–1075. doi:10.1016/j.marpolbul.2003.12.012

Eilander Architects, 2010. Plastic Island [WWW Document]. Plast. Isl. URL http://www.plasticisland.org/about.html (accessed 7.14.16).

Enders, K., Lenz, R., Stedmon, C.A., Nielsen, T.G., 2015. Abundance, size and polymer composition of marine microplastics ≥ 10 μm in the Atlantic Ocean and their modelled vertical distribution. Mar. Pollut. Bull. 100, 70–81. doi:10.1016/j.marpolbul.2015.09.027

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. PLoS ONE 9, e111913. doi:10.1371/journal.pone.0111913

Eriksson, C., Burton, H., Fitch, S., Schulz, M., van den Hoff, J., 2013. Daily accumulation rates of marine debris on sub-Antarctic island beaches. Mar. Pollut. Bull. 66, 199–208. doi:10.1016/j.marpolbul.2012.08.026

EU Comission, 2016. TOOL #15: The choice of policy instruments [WWW Document]. Better Regul. - Eur. Comm. URL http://ec.europa.eu/smart-regulation/guidelines/tool_15_en.htm (accessed 1.29.17).

EU Meeresstrategie- Rahmenrichtlinie, 2008. EU Parlament und Rat, Directive 2008/56/EC.

eVolo Architecture Magazine, 2014. Seawer: The Garbage-Seascraper- eVolo | Architecture Magazine [WWW Document]. EVolo - Archit. Mag. URL http://www.evolo.us/competition/seawer-the-garbage-seascraper/ (accessed 7.14.16).

Fazey, F.M.C., Ryan, P.G., 2016. Biofouling on buoyant marine plastics: An experimental study into the effect of size on surface longevity. Environ. Pollut. 210, 354–360. doi:10.1016/j.envpol.2016.01.026

Felt, U., Hofmann, T., Vogel, W., Gerdts, G., Herndl, G.J., 2017. Mikroplastik: Weit verbreitet – und wie gefährlich?

Galbreth, M.R., Ghosh, B., 2013. Competition and Sustainability: The Impact of Consumer Awareness. Decis. Sci. 44, 127–159. doi:10.1111/j.1540-5915.2012.00395.x

Galgani, F., Hanke, G., Maes, T., 2015. Global Distribution, Composition and Abundance of Marine Litter, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 29–56. doi:10.1007/978-3-319-16510-3_2

Galgani, F., Leaute, J.P., Moguedet, P., Souplet, A., Verin, Y., Carpentier, A., Goraguer, H., Latrouite, D., Andral, B., Cadiou, Y., others, 2000. Litter on the sea floor along European coasts. Mar. Pollut. Bull. 40, 516–527.

Galil, B.., Golik, A., Türkay, M., 1995. Litter at the Bottom of the Sea: A Sea Bed Survey in the Eastern Mediterranean. Mar. Pollut. Bull. 30.

Galloway, T.S., 2015. Micro- and Nano-plastics and Human Health, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 343–366. doi:10.1007/978-3-319-16510-3_13

Gebauer, M., Stannard, D., 1995. Vergasung von Altkunststoffen, in: Die Wiederverwertung von

Kunststoffen. Carl Haser Verlag München Wien, München Wien, pp. 463–489.
Generalic, E., 2017. Internationale Einheitensystem (SI) [WWW Document]. EniG Periodensystem Elem. URL http://www.periodni.com/de/internationale_einheitensystem.html (accessed 7.7.17).
Giannoutsos, S.V., Manias, S.N., 2013. Development of an integrated energy efficiency control system for ship power balance and diesel generator fuel consumption optimization, in: Industry Applications Society Annual Meeting, 2013 IEEE. IEEE, pp. 1–11.
Gohary, M.M.E., Seddiek, I.S., 2013. Utilization of alternative marine fuels for gas turbine power plant onboard ships. Int. J. Nav. Archit. Ocean Eng. 5, 21–32. doi:10.2478/IJNAOE-2013-0115
Goodship, V., 2007. Introduction to plastics recycling. iSmithers Rapra Publishing.
Gouin, T., Roche, N., Lohmann, R., Hodges, G., 2011. A Thermodynamic Approach for Assessing the Environmental Exposure of Chemicals Absorbed to Microplastic. Environ. Sci. Technol. 45, 1466–1472. doi:10.1021/es1032025
Great Pacific Garbage Patch - National Geographic Education [WWW Document], n.d. URL http://education.nationalgeographic.org/encyclopedia/great-pacific-garbage-patch/ (accessed 2.18.16).
Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings--entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos. Trans. R. Soc. B Biol. Sci. 364, 2013–2025. doi:10.1098/rstb.2008.0265
Halden, R.U., 2010. Plastics and Health Risks. Annu. Rev. Public Health 31, 179–194. doi:10.1146/annurev.publhealth.012809.103714
Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. Environ. Sci. Technol. 46, 3060–3075. doi:10.1021/es2031505
Hoornweg, D., Bhada-Tata, P., 2012. What a Waste : A Global Review of Solid Waste Management. World Bank Wash. DC, Urban development series knowledge papers.
IMO (International Maritime Organization), n.d. International Convention for the Prevention of Pollution from Ships (MARPOL) [WWW Document]. URL http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx (accessed 1.7.17).
Ivar do Sul, J.A., Costa, M.F., 2007. Marine debris review for Latin America and the Wider Caribbean Region: From the 1970s until now, and where do we go from here? Mar. Pollut. Bull. 54, 1087–1104. doi:10.1016/j.marpolbul.2007.05.004
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771. doi:10.1126/science.1260352
Jang, Y.C., Hong, S., Lee, J., Lee, M.J., Shim, W.J., 2014. Estimation of lost tourism revenue in Geoje Island from the 2011 marine debris pollution event in South Korea. Mar. Pollut. Bull. 81, 49–54. doi:10.1016/j.marpolbul.2014.02.021
Jang, Y.C., Song, B.J., 2013. A Critical Analysis of the Rationality of South Korea’s Marine Debris Policy. Int. J. Policy Stud. 4, 83–105.
Jayaraman, K., Haron, H., Sung, G.B., Lin, S.K., 2011. Consumer reflections on the usage of plastic bags to parcel hot edible items: an empirical study in Malaysia. J. Clean. Prod. 19, 1527–1535. doi:10.1016/j.jclepro.2011.03.019
Jovanović, S., Dzunuzović, J.V., Stojanović, Z., 2013. Polymers Based on Renewable Raw Materials – Part I. Kem. U Ind. 62, 307–314.
Kaiser, J., 2010. The Dirt on Ocean Garbage Patches. Science 328, 1506–1506. doi:10.1126/science.328.5985.1506
Kantarelis, E., Donaj, P., Yang, W., Zabaniotou, A., 2009. Sustainable valorization of plastic wastes for energy with environmental safety via High-Temperature Pyrolysis (HTP) and High-Temperature Steam Gasification (HTSG). J. Hazard. Mater. 167, 675–684. doi:10.1016/j.jhazmat.2009.01.036
Kiessling, T., Gutow, L., Thiel, M., 2015. Marine Litter as Habitat and Dispersal Vector, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 141–181. doi:10.1007/978-3-319-16510-3_6
Kim, J.-W., Mun, T.-Y., Kim, J.-O., Kim, J.-S., 2011. Air gasification of mixed plastic wastes using a two-stage gasifier for the production of producer gas with low tar and a high caloric value. Fuel 90, 2266–2272. doi:10.1016/j.fuel.2011.02.021
Kirbach, R., 2015. Plastikmüll: Im Plastik gefangen. Zeit.
Koelmans, A.A., 2015. Modeling the Role of Microplastics in Bioaccumulation of Organic Chemicals to Marine Aquatic Organisms. A Critical Review, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 309–324. doi:10.1007/978-3-319-16510-3_11
Koelmans, A.A., Besseling, E., Shim, W.J., 2015. Nanoplastics in the Aquatic Environment. Critical Review, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International

Publishing, pp. 325–340. doi:10.1007/978-3-319-16510-3_12

Kołwzan, K., Narewski, M., 2012. Alternative Fuels for Marine Applications. Latv. J. Chem. 51. doi:10.2478/v10161-012-0024-9

Kordella, S., Geraga, M., Papatheodorou, G., Fakiris, E., Mitropoulou, I.M., 2013. Litter composition and source contribution for 80 beaches in Greece, Eastern Mediterranean: A nationwide voluntary clean-up campaign. Aquat. Ecosyst. Health Manag. 16, 111–118.

Kühn, S., Rebolledo, E.L.B., Franeker, J.A. van, 2015. Deleterious Effects of Litter on Marine Life, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 75–116. doi:10.1007/978-3-319-16510-3_4

Kunwar, B., Cheng, H.N., Chandrashekaran, S.R., Sharma, B.K., 2016. Plastics to fuel: a review. Renew. Sustain. Energy Rev. 54, 421–428. doi:10.1016/j.rser.2015.10.015

Lattin, G.L., Moore, C.J., Zellers, A.F., Moore, S.L., Weisberg, S.B., 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Mar. Pollut. Bull. 49, 291–294. doi:10.1016/j.marpolbul.2004.01.020

Lebreton, L.C.-M., Greer, S.D., Borrero, J.C., 2012. Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull. 64, 653–661. doi:10.1016/j.marpolbul.2011.10.027

Lee, D.-I., Cho, H.-S., Jeong, S.-B., 2006. Distribution characteristics of marine litter on the sea bed of the East China Sea and the South Sea of Korea. Estuar. Coast. Shelf Sci. 70, 187–194. doi:10.1016/j.ecss.2006.06.003

Leonard, T.C., 2008. Richard H. Thaler, Cass R. Sunstein, Nudge: Improving decisions about health, wealth, and happiness: Yale University Press, New Haven, CT, 2008, 293 pp, $26.00. Const. Polit. Econ. 19, 356–360. doi:10.1007/s10602-008-9056-2

Lithner, D., Larsson, Å., Dave, G., 2011. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Sci. Total Environ. 409, 3309–3324. doi:10.1016/j.scitotenv.2011.04.038

Liubartseva, S., Coppini, G., Lecci, R., Creti, S., 2016. Regional approach to modeling the transport of floating plastic debris in the Adriatic Sea. Mar. Pollut. Bull. 103, 115–127. doi:10.1016/j.marpolbul.2015.12.031

Löder, M.G.J., Gerdts, G., 2015. Methodology Used for the Detection and Identification of Microplastics—A Critical Appraisal, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 201–227. doi:10.1007/978-3-319-16510-3_8

London Protocol, 2006. 1996 Protocol to the convention on the prevention of Marine Pollution by dumping of wastes and other Matter, 1972.

López, A., de Marco, I., Caballero, B.M., Laresgoiti, M.F., Adrados, A., 2011. Dechlorination of fuels in pyrolysis of PVC containing plastic wastes. Fuel Process. Technol., III International Congress on Energetic Engineering and Environment 92, 253–260. doi:10.1016/j.fuproc.2010.05.008

López, A., de Marco, I., Caballero, B.M., Laresgoiti, M.F., Adrados, A., 2010. Pyrolysis of municipal plastic wastes: Influence of raw material composition. Waste Manag. 30, 620–627. doi:10.1016/j.wasman.2009.10.014

Lundquist, L., 2000. Life Cycle Engineering of Plastics: Technology, Economy and Environment, 1st ed. Elsevier Science, Oxford.

Lusher, A., 2015. Microplastics in the Marine Environment: Distribution, Interactions and Effects, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 245–307. doi:10.1007/978-3-319-16510-3_10

Marine Litter Solutions, n.d. Joint Declaration [WWW Document]. Mar. Litter Solut. URL https://www.marinelittersolutions.com/about-us/joint-declaration/ (accessed 9.8.16).

Martens, H., 2011. Recyclingtechnik: Fachbuch für Lehre und Praxis. Spektrum, Akad. Verl, Heidelberg.

Martinez-Ribes, L., Basterretxea, G., Palmer, M., Tintoré, J., 2007. Origin and abundance of beach debris in the Balearic Islands. Sci. Mar. 71, 305–314.

Martini, 2014. The Ocean Cleanup, Part 2: Technical review of the feasibility study [WWW Document]. Deep Sea News. URL http://www.deepseanews.com/2014/07/the-ocean-cleanup-part-2-technical-review-of-the-feasibility-study/ (accessed 2.18.16).

Maximenko, N., Hafner, J., Niiler, P., 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. Mar. Pollut. Bull., At-sea Detection of Derelict Fishing Gear 65, 51–62. doi:10.1016/j.marpolbul.2011.04.016

McIlgorm, A., Campbell, H.F., Rule, M.J., 2011. The economic cost and control of marine debris damage in the Asia-Pacific region. Ocean Coast. Manag. 54, 643–651. doi:10.1016/j.ocecoaman.2011.05.007

McIntosh, R.R., Kirkwood, R., Sutherland, D.R., Dann, P., 2015. Drivers and annual estimates of marine wildlife entanglement rates: A long-term case study with Australian fur seals. Mar. Pollut. Bull. 101, 716–725. doi:10.1016/j.marpolbul.2015.10.007

Milhé, M., van de Steene, L., Haube, M., Commandré, J.-M., Fassinou, W.-F., Flamant, G., 2013. Autothermal and allothermal pyrolysis in a continuous fixed bed reactor. J. Anal. Appl. Pyrolysis 103, 102–111. doi:10.1016/j.jaap.2013.03.011

Mitchell, A., 2015. Thinking without the ‘circle’: Marine plastic and global ethics. Polit. Geogr. 47, 77–85. doi:10.1016/j.polgeo.2015.04.003

MKinsey Center for Business and Environment, 2015. Stemming the Tide: Land-based strategies for a plastic-free ocean.

Mobilik, J.-M., Ling, T.-Y., Husain, M.-L.B., Hassan, R., 2015. Seasonal trends in abundance and composition of marine debris in selected public beaches in Peninsular Malaysia, in: AIP Conference Proceedings. Presented at the THE 2015 UKM FST POSTGRADUATE COLLOQUIUM: Proceedings of the Universiti Kebangsaan Malaysia, Faculty of Science and Technology 2015 Postgraduate Colloquium, AIP Publishing, p. 020020. doi:10.1063/1.4931205

Moore, C.J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environ. Res. 108, 131–139. doi:10.1016/j.envres.2008.07.025

Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A Comparison of Plastic and Plankton in the North Pacific Central Gyre. Mar. Pollut. Bull. 42, 1297–1300. doi:10.1016/S0025-326X(01)00114-X

Moore, C.J., Moore, S.L., Weisberg, S.B., Lattin, G.L., Zellers, A.F., 2002. A comparison of neustonic plastic and zooplankton abundance in southern California’s coastal waters. Mar. Pollut. Bull. 44, 1035–1038. doi:10.1016/S0025-326X(02)00150-9

Moore, S.L., Gregorio, D., Carreon, M., Weisberg, S.B., Leecaster, M.K., 2001. Composition and Distribution of Beach Debris in Orange County, California. Mar. Pollut. Bull. 42, 241–245. doi:10.1016/S0025-326X(00)00148-X

Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C.M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Mar. Pollut. Bull. 60, 1873–1878. doi:10.1016/j.marpolbul.2010.07.020

Nakashima, E., Isobe, A., Kako, S., Itai, T., Takahashi, S., 2012. Quantification of Toxic Metals Derived from Macroplastic Litter on Ookushi Beach, Japan. Environ. Sci. Technol. 120904130154007. doi:10.1021/es301362g

Nash, A.D., 1992. Impacts of marine debris on subsistence fishermen An exploratory study. Mar. Pollut. Bull. 24, 150–156. doi:10.1016/0025-326X(92)90243-Y

Newman, S., Watkins, E., Farmer, A., Brink, P. ten, Schweitzer, J.-P., 2015. The Economics of Marine Litter, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 367–394.

OANDA, 2017. Währungsrechner [WWW Document]. URL https://www.oanda.com/lang/de/currency/converter/ (accessed 7.14.17).

ocean cleanup, n.d. ocean cleanup A deep dive into plastic flow modeling [WWW Document]. Ocean Cleanup Dev. Technol. Extr. Prev. Intercept Plast. Pollut. URL http://www.theoceancleanup.com/blog/show/item/a-deep-dive-into-plastic-flow-modeling.html (accessed 6.20.16).

Ocean Conservancy, 2016. 30th anniversary International Coastl cleanup - annual report [WWW Document]. URL http://www.oceanconservancy.org/our-work/marine-debris/2016-data-release/2016-data-release-1.pdf (accessed 12.19.16).

OECD, n.d. Extended producer responsibility [WWW Document]. URL http://www.oecd.org/env/tools-evaluation/extendedproducerresponsibility.htm (accessed 2.6.17).

Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., Jagnytsch, O., Lutz, I., Kusk, K.O., Wollenberger, L., Santos, E.M., Paull, G.C., Van Look, K.J.W., Tyler, C.R., 2009. A critical analysis of the biological impacts of plasticizers on wildlife. Philos. Trans. R. Soc. B Biol. Sci. 364, 2047–2062. doi:10.1098/rstb.2008.0242

Oosterhuis, F., Papyrakis, E., Boteler, B., 2014. Economic instruments and marine litter control. Ocean Coast. Manag. 102, Part A, 47–54. doi:10.1016/j.ocecoaman.2014.08.005

OSPAR Commission, 2014. Regional Action Plan (RSP) for Marine Litter.

OSPAR Commission, n.d. About [WWW Document]. OSPAR Comm. URL https://www.ospar.org/about (accessed 7.7.17).

Panda, A.K., Singh, R.K., Mishra, D.K., 2010. Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products—A world prospective. Renew. Sustain. Energy Rev. 14, 233–248. doi:10.1016/j.rser.2009.07.005

Pham, C.K., Ramirez-Llodra, E., Alt, C.H.S., Amaro, T., Bergmann, M., Canals, M., Company, J.B., Davies, J., Duineveld, G., Galgani, F., Howell, K.L., Huvenne, V.A.I., Isidro, E., Jones, D.O.B., Lastras, G., Morato, T., Gomes-Pereira, J.N., Purser, A., Stewart, H., Tojeira, I., Tubau, X., Van Rooij, D., Tyler, P.A., 2014. Marine Litter Distribution and Density in European Seas, from the Shelves to Deep Basins. PLoS ONE 9, e95839. doi:10.1371/journal.pone.0095839

PK-Nr. 537/2015, 2015. Nationalrat: Plastik hat in der Umwelt nichts verloren [WWW Document]. URL https://www.parlament.gv.at/PAKT/PR/JAHR_2015/PK0537/index.shtml (accessed 5.25.16).

Plastic Whale, 2016. Be part of the solution for plastic-free waters! [WWW Document]. Plast. Whale. URL http://plasticwhale.com/ (accessed 10.18.16).

PlasticsEurope - Association of Plastics Manufacturers, 2015. Plastics - the Facts 2015 - An analysis of European plastics production, demand and waste data.

Revill, A.S., Dunlin, G., 2003. The fishing capacity of gillnets lost on wrecks and on open ground in UK coastal waters. Fish. Res. 64, 107–113. doi:10.1016/S0165-7836(03)00209-1

Rochman, C.M., 2015. The Complex Mixture, Fate and Toxicity of Chemicals Associated with Plastic Debris in the Marine Environment, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 117–140. doi:10.1007/978-3-319-16510-3_5

Roos Lundström, F., Måartensson, A., 2015. The Journey of Plastic trough Oceans: A study on quantifying micro plastic particles in ocean outside Costa Rican west coast.

Rudnik, E., 2008. Chapter 6 - Biodegradability testing of compostable polymer materials, in: Compostable Polymer Materials. Elsevier, Amsterdam, pp. 112–166. doi:10.1016/B978-008045371-2.50008-1

Ryan, P.G., 2015. A Brief History of Marine Litter Research, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 1–25. doi:10.1007/978-3-319-16510-3_1

Schröfl, C., 2016. Untersuchung, in: Plastikinseln Im Meer. Höhere Lehranstalt für Elektrotechnik, Wien.

Sheavly, S.B., Register, K.M., 2007. Marine Debris & Plastics: Environmental Concerns, Sources, Impacts and Solutions. J. Polym. Environ. 15, 301–305. doi:10.1007/s10924-007-0074-3

Smailys, V., Daukšys, V., Zamiatina, N., 2016. The Experimental Research of Additional Energy Consumption and Exhaust Gas Emissions from Use of Marine Litter Collecting Nets. Procedia Eng. 134, 205–214. doi:10.1016/j.proeng.2016.01.061

Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Shim, W.J., 2015. Occurrence and Distribution of Microplastics in the Sea Surface Microlayer in Jinhae Bay, South Korea. Arch. Environ. Contam. Toxicol. 69, 279–287. doi:10.1007/s00244-015-0209-9

Stengel, O., 2011. Suffizienz: die Konsumgesellschaft in der ökologischen Krise, Wuppertaler Schriften zur Forschung für eine nachhaltige Entwicklung. Oekom, München.

Strafella, P., Fabi, G., Spagnolo, A., Grati, F., Polidori, P., Punzo, E., Fortibuoni, T., Marceta, B., Raicevich, S., Cvitkovic, I., Despalatovic, M., Scarcella, G., 2015. Spatial pattern and weight of seabed marine litter in the northern and central Adriatic Sea. Mar. Pollut. Bull. 91, 120–127. doi:10.1016/j.marpolbul.2014.12.018

Tabasová, A., Kropáč, J., Kermes, V., Nemet, A., Stehlík, P., 2012. Waste-to-energy technologies: Impact on environment. Energy 44, 146–155. doi:10.1016/j.energy.2012.01.014

Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., Watanuki, Y., 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. 69, 219–222. doi:10.1016/j.marpolbul.2012.12.010

Thompson, R.C., 2015. Microplastics in the Marine Environment: Sources, Consequences and Solutions, in: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, pp. 185–200. doi:10.1007/978-3-319-16510-3_7

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at Sea: Where Is All the Plastic? Science 304, 838–838. doi:10.1126/science.1094559

Thornton, L., Jackson, N.L., 1998. Spatial and temporal variations in debris accumulation and composition on an estuarine shoreline, Cliffwood Beach, New Jersey, USA. Mar. Pollut. Bull. 36, 705–711. doi:10.1016/S0025-326X(98)00041-1

Topçu, E.N., Öztürk, B., 2010. Abundance and composition of solid waste materials on the western part of the Turkish Black Sea seabed. Aquat. Ecosyst. Health Manag. 13, 301–306. doi:10.1080/14634988.2010.503684

Turner, A., Solman, K.R., 2016. Analysis of the elemental composition of marine litter by field-portable-XRF. Talanta 159, 262–271. doi:10.1016/j.talanta.2016.06.026

Umuhire, M.L., Fang, Q., 2016. Method and application of ocean environmental awareness measurement: Lessons learnt from university students of China. Mar. Pollut. Bull., Integrated Coastal Management: Lessons Learned to Address New Challenges 102, 289–294. doi:10.1016/j.marpolbul.2015.07.067

UN, 2013. Overview - Convention & Related Agreements [WWW Document]. U. N. Conv. Law Sea 10 Dec. 1982 Overv. Full Text. URL http://www.un.org/depts/los/convention_agreements/convention_overview_convention.htm (accessed 2.19.17).

UNEP, 2009. Guidelines on the use of market-based instruments to address the problem of marine litter. UNEP, Nairobi.

UNEP, 2005. UNEP Regional Seas Programme, Marine Litter And Abandoned Fishing Gear. Reg. Seas Coord Atin G Off. 1–30.

UNEP, n.d. About the Cartagena Convention — Caribbean Environment Programme [WWW Document].

URL http://www.cep.unep.org/cartagena-convention/about-the-cartagena-convention (accessed 9.8.16a).

UNEP, n.d. Assessment & Management of Environmental Pollution (AMEP) — Caribbean Environment Programme [WWW Document]. URL http://www.cep.unep.org/content/about-cep/amep (accessed 9.8.16b).

UNEP (United Nations Environment Programme), 2009. Stockholm convention on persistent organic pollutants.

Urban, D., 1986. Was ist Umweltbewußtsein? Z. Für Soziol. ZfS 15, 363–377.

Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbens, J., Janssen, C.R., 2015. Microplastics in sediments: A review of techniques, occurrence and effects. Mar. Environ. Res. 111, 5–17. doi:10.1016/j.marenvres.2015.06.007

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. Environ. Res. Lett. 10, 124006. doi:10.1088/1748-9326/10/12/124006

Vasudeo, R.A., Abitha, V.K., Vinayak, K., Jayaja, P., Gaikwad, S., 2016. Sustainable Development Through Feedstock Recycling of Plastic Wastes. Macromol. Symp. 362, 39–51. doi:10.1002/masy.201500107

Walendziewski, J., 2002. Engine fuel derived from waste plastics by thermal treatment. Fuel 81, 473–481.

Wallace-wells, B., 2010. Cass Sunstein Wants to Nudge Us. N. Y. Times.

Wilcox, C., Heathcote, G., Goldberg, J., Gunn, R., Peel, D., Hardesty, B.D., 2015. Understanding the sources and effects of abandoned, lost, and discarded fishing gear on marine turtles in northern Australia. Conserv. Biol. 29, 198–206. doi:10.1111/cobi.12355

Williams, A.T., Rangel-Buitrago, N.G., Anfuso, G., Cervantes, O., Botero, C.M., 2016. Litter impacts on scenery and tourism on the Colombian north Caribbean coast. Tour. Manag. 55, 209–224. doi:10.1016/j.tourman.2016.02.008

Wong, C.S., Green, D.R., Cretney, W.J., 1974. Quantitative Tar and Plastic Waste Distributions in the Pacific Ocean. Nature 247, 30–32. doi:10.1038/247030a0

Wong, S.L., Ngadi, N., Abdullah, T.A.T., Inuwa, I.M., 2015. Current state and future prospects of plastic waste as source of fuel: A review. Renew. Sustain. Energy Rev. 50, 1167–1180. doi:10.1016/j.rser.2015.04.063

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: A review. Environ. Pollut. 178, 483–492. doi:10.1016/j.envpol.2013.02.031

Wu, C., Williams, P.T., 2010. Pyrolysis–gasification of plastics, mixed plastics and real-world plastic waste with and without Ni–Mg–Al catalyst. Fuel 89, 3022–3032. doi:10.1016/j.fuel.2010.05.032

Wu, C., Williams, P.T., 2009. Hydrogen production by steam gasification of polypropylene with various nickel catalysts. Appl. Catal. B Environ. 87, 152–161. doi:10.1016/j.apcatb.2008.09.003

Yamashita, R., Tanimura, A., 2007. Floating plastic in the Kuroshio Current area, western North Pacific Ocean. Mar Pollut Bull 54, 485–488.

Yang, C.Z., Yaniger, S.I., Jordan, V.C., Klein, D.J., Bittner, G.D., 2011. Most Plastic Products Release Estrogenic Chemicals: A Potential Health Problem That Can Be Solved. Environ. Health Perspect. 119, 989–996. doi:10.1289/ehp.1003220

Yau, P.S., Lee, S.-C., Ho, K.F., 2012. Speed Profiles for Improvement of Maritime Emission Estimation. Environ. Eng. Sci. 29, 1076–1084. doi:10.1089/ees.2011.0399

Yoon, J.-H., Kawano, S., Igawa, S., 2010. Modeling of marine litter drift and beaching in the Japan Sea. Mar. Pollut. Bull. 60, 448–463. doi:10.1016/j.marpolbul.2009.09.033

Zhou, P., Huang, C., Fang, H., Cai, W., Li, D., Li, X., Yu, H., 2011. The abundance, composition and sources of marine debris in coastal seawaters or beaches around the northern South China Sea (China). Mar. Pollut. Bull. 62, 1998–2007. doi:10.1016/j.marpolbul.2011.06.018

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