Allseas' riverine plastic litter recovery system

Environmental impact assessment

PRé

Fact-based sustainability

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Non-technical summary

Context

As part of the European Union funded LIFE SouPLess project, Allseas has developed, manufactured and operated two riverine plastic collection systems. An environmental impact assessment study is executed by PRé Sustainability for one of the two systems, called ‘Catchy’. The assessment was done both qualitatively and quantitatively. In the qualitative part of the study literature was consulted for environmental issues that could not be assessed in the later quantitative part as well as applicable regulations. In the quantitative part of the study and life cycle assessment study was done for Catchy.

Qualitative assessment

Consulted literature underlined that river, including the Rhine River, are responsible of transporting large quantities of plastic particles into the marine environment every year. In the marine environment plastic harms flora and fauna in five predominant ways:

- Entanglement
- Ingestion
- Chemical leaching and binding of toxins
- Habitat loss
- Rafting

There is no evidence that the riverine flora and fauna are not harmed by plastics similarly.

Due to its mainly fossil source, the production of virgin plastics is responsible for significant share of the global carbon footprint. The production of plastics is expected to further increase in the coming years, thereby emitting even more greenhouse gasses and, without proper waste collection and treatment, harming more flora and fauna in the future.

A consultation of applicable regulations in the Netherlands and Europe did not lead to the expectation that the riverine plastic collection systems lead to any violations of rules.

Quantitative assessment

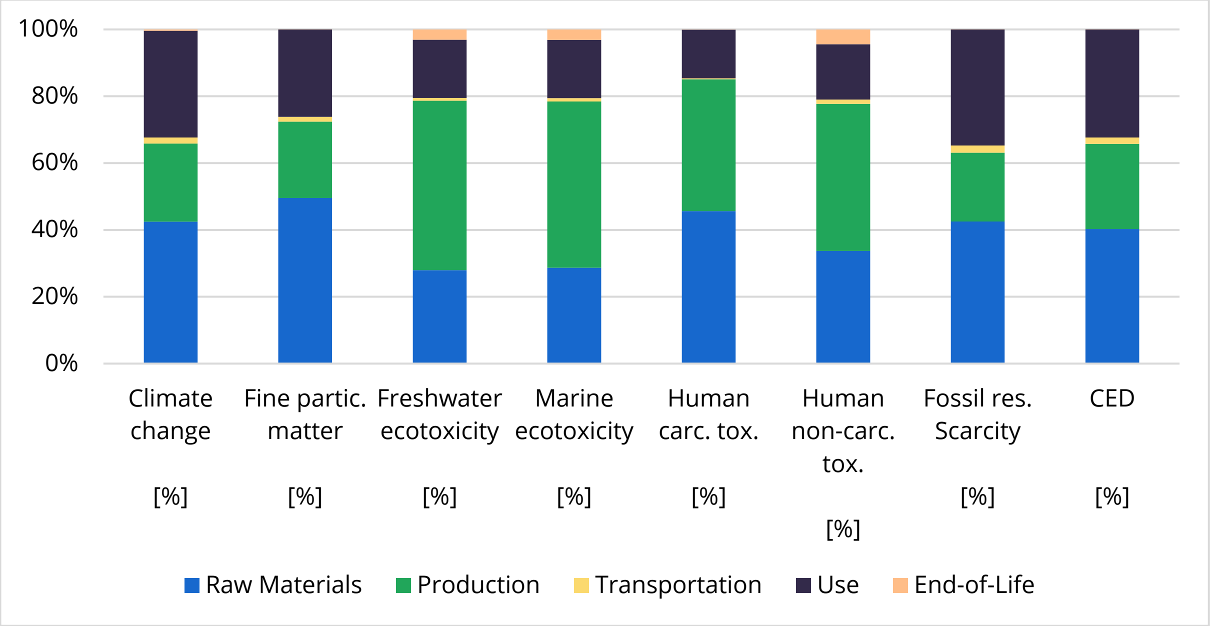
A life cycle assessment (LCA) was executed to quantify the environmental impact of the riverine plastic collection system ‘Catchy’. The results are used to further guide the design process of the system.

Catchy is a passive collection system in the Vijfhuizerhaven, a harbor close to Rotterdam. The system comprises four elements: two floating booms, a floating frame and collection cage. The floating booms, 200 m and 12 m in length, guide waste under the effect of the wind and currents towards the collection cage. Both booms are equipped with an underwater skirt to catch both surface and submerged waste. The floating frame is secured to piles that allow it to move vertically with the tides. The plastic is trapped into the cage that is emptied every month. The primary function of the system is to collect plastic from the river, however, an unwanted secondary function is the collection of biomass in significant amounts.

The system's environmental impact was evaluated for the collection of 120 kg riverine plastic per year. In the study one Catchy system is considered to be enough to catch that amount of plastic annually.

The system was evaluated from cradle-to-grave: from the extraction of raw materials, through the production of the part and the system, the use phase to the end-of-life of the system.

The assessment showed that the majority of the environmental impact of Catchy comes from the raw material extraction, the production of its parts and use & maintenance of the system. These three life cycle phases accounted for at least 94% of the environmental impact in all impact categories.



Relative characterized results for the most relevant impacts categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection, grouped per life cycle phase

The impact of the raw material extraction for and the production is mainly for steel parts, the impact of steel parts represent at least 45% for all impact categories. The environmental impact from the steel parts is however lower than its contribution to the total mass, since 87% of the mass of the system is steel. The impact during the use phase is mainly for the use of the crane to lift the cage out of the system monthly.

Additional grouping and sensitivity and uncertainty analyses were done to obtain further insights in the environmental impact of Catchy and to increase the understanding of the results.

The system was additionally evaluated including the avoidance of emissions of producing virgin plastics when recycling the collected plastic. These emissions were included as negative emissions. The assessment showed that the additional environmental impact for the maintenance of the system is only lower than the avoided impact from virgin plastic production for a yield of at least 10 kg per month. The riverine plastic collection system has the potential of being environmentally neutral or even positive for fossil resource scarcity and cumulative energy demand, when achieving the theoretical maximum yield of 64 kg plastic per month. A net-zero impact for climate change is only achievable for yields above the theoretical maximum.

To improve the environmental performance of the system, several opportunities are identified:

1. Optimizing the emptying of cages. Since the crane use has been identified as the main source of environmental impact.
2. Fit for purpose: reduce the amount of steel. Since the use of steel has been identified as another significant source of environmental impact.
3. Use of recycled steel instead of virgin steel. Since the use of steel has been identified as another significant source of environmental impact.

Conclusions

When considering the results from the quantitative study separately from the qualitative ones, it cannot be concluded unambiguously that Catchy is environmentally beneficial. For the current yield, the avoided environmental impact from virgin plastic production is lower than the environmental impact from Catchy. In other words, Catchy does have a net environmental impact. However, when including also the added environmental benefits identified in the qualitative study, Catchy delivers a positive contribution to the environment. The quantitative study also stressed the importance of either decreasing use of steel or crane use, or increasing the yield to have a net zero impact for at least the fossil resource scarcity and cumulative energy demand impact category, and potentially also climate change and fine particulate matter.

Disclaimer

It is important to point out that the results which are presented in this report have not undergone third party verification. None of the chapters or underlying models have been peer-reviewed by (an) independent critical reviewer(s); only internal quality assurance by service provider (PRé) and commissioner (Allseas). The results of the Screening LCA are unique for the data of the selected systems and the methodological choices and assumptions which have been made in this study. Therefore, the results are not meant for comparisons with other countries or other collecting systems, and can be used for internal communication only.

1 Introduction

At the moment Allseas has developed, manufactured and operated two riverine plastic collection systems (further referred to as 'collection system': "Patje Plastic" in Antwerp, Belgium, and "Catchy" near Rotterdam, the Netherlands. This study will focus on the Catchy collection system.

The collection system is part of the European Union funded project LIFE SouPLess. The current report describes the 'assessment of a planned activity on the environment', a so-called environmental impact assessment.[1] We thereby focus both on the burdens of operating such a system, for which a *quantitative* LCA study is performed, see chapter 4, and the benefits of the removal of plastic, for which a more *qualitative* literature study is performed, see chapter 3.

2 Environmental issues

2.1 Climate Change

The collection of plastics from rivers does not only benefit flora and fauna as described in section 3. Whenever the collected plastic can be recycled properly, the production of virgin plastics can be avoided. The production of both virgin and recycled plastics causes several gaseous emissions. There are several of those gaseous emissions that cause global warming, including carbon dioxide, methane, nitrous oxides and fluorinated gases. In general, the production of virgin plastics emits more of these gasses than the production of recycled plastics. The climate change impact category combines the effect of the periods of time that the various greenhouse gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. For climate change, the damage modelling is subdivided into several steps, see Figure 1. An emission of a greenhouse gas will lead to an increased atmospheric concentration of greenhouse gases which, in turn, will increase the radiative forcing capacity of the atmosphere, leading to an increase in the global mean temperature. The increased temperature influences diseases, flooding, biomes and rivers. Through the effects in these, climate change ultimately results in damage to human health and ecosystems.

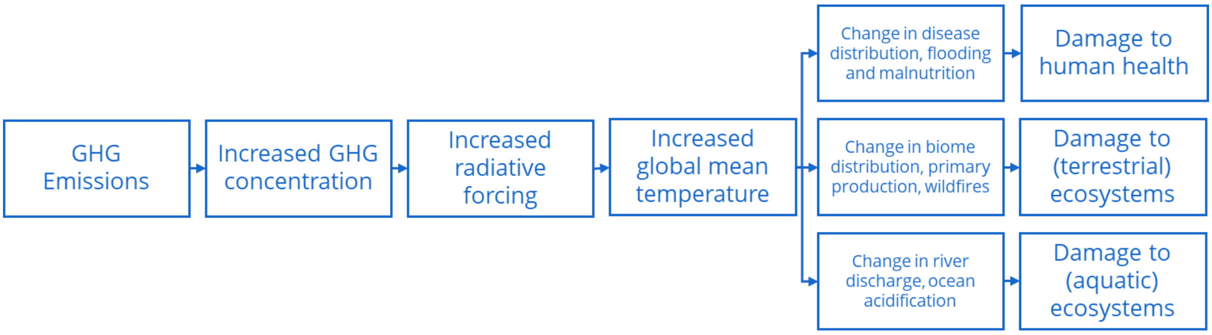


Figure 1 Causse-effect pathway for the climate change impact category.

2.2 Ecotoxicity and human toxicity

When plastic litter decomposes, toxic compounds might be leached into either water or into soils, see section 3.1.1 and 3.1.3. Toxic compounds are considered in the toxicity related impact categories: ecotoxicity, i.e., toxicity towards animals and human toxicity, i.e., toxicity towards humans. Ecotoxicity can be further subdivided by the compartments in which the toxicity takes place, for example freshwater, marine and terrestrial, depending on where the chemical fate of the toxins is. The further refinement of these compartments is still work in progress. For human toxicity a distinction is made between carcinogenic and non-carcinogenic toxicity. The characterization of human toxicity and ecotoxicity environmental impact accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Figure 2 shows the cause-effect pathway, from emission to the environment, via fate and exposure, to affected species and disease incidences, leading to damage to ecosystems and human health.

It is important to note that the leaching of toxins by plastic litter is only covered qualitatively in section 3, while the leaching by Catchy is assumed to be negligible. Characterized impact for the toxicities are coming from the emissions of chemicals throughout the remainder of the life cycle of Catchy.

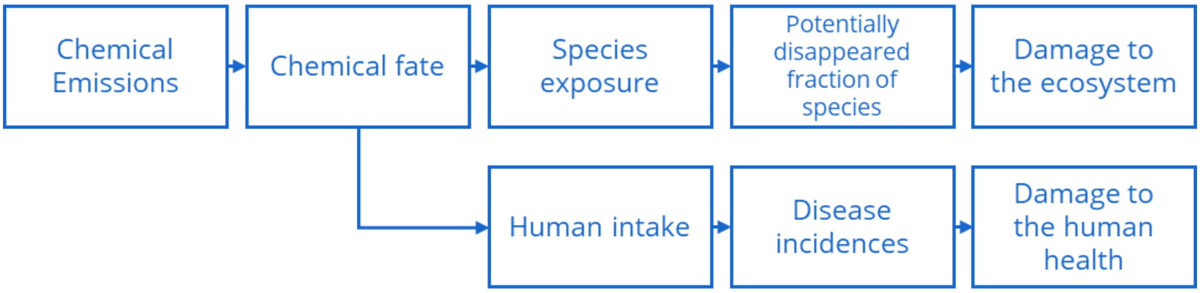


Figure 2 Cause-effect pathway for the toxicity impact categories

2.3 Resource use

As explained earlier, the collection of plastics from rivers can result in an avoidance of the production of virgin plastics. Virgin plastics are primarily made of oil and natural gas. Both are fossil resources with a limited availability.

For the impact category fossil resource scarcity, the damage modelling is subdivided, see Figure 3. It is assumed that fossil fuels with the lowest costs are extracted first. Consequently, the increase in fossil fuel extraction causes an increase in costs due either to a change in production technique or to sourcing from a costlier location. For example, when all conventional oil is depleted, alternative techniques, such as enhanced oil recovery, will be applied or oil will be produced in alternative geographical locations with higher costs. This, when combined with the expected future extraction of a fossil resource, leads to a surplus cost. Here, see section 4.1.2, on page 23, we estimated the damage to natural resource scarcity.

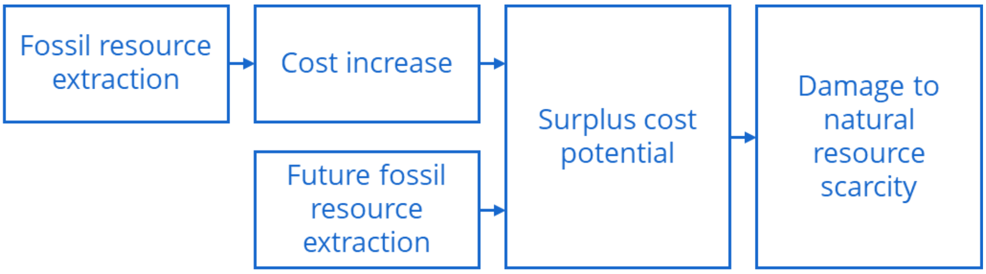


Figure 3 Cause-effect pathway for the toxicity impact categories

2.4 Biodiversity

Biodiversity is defined as *"the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems"*.[2] It thus describes the natural variation of species. Mankind relies on biodiversity and ecosystems in many ways, through the so-called 'ecosystem services'. The services that ecosystems provide can be categorized by supporting, provisioning, regulating or cultural services, see Figure 4.[3]

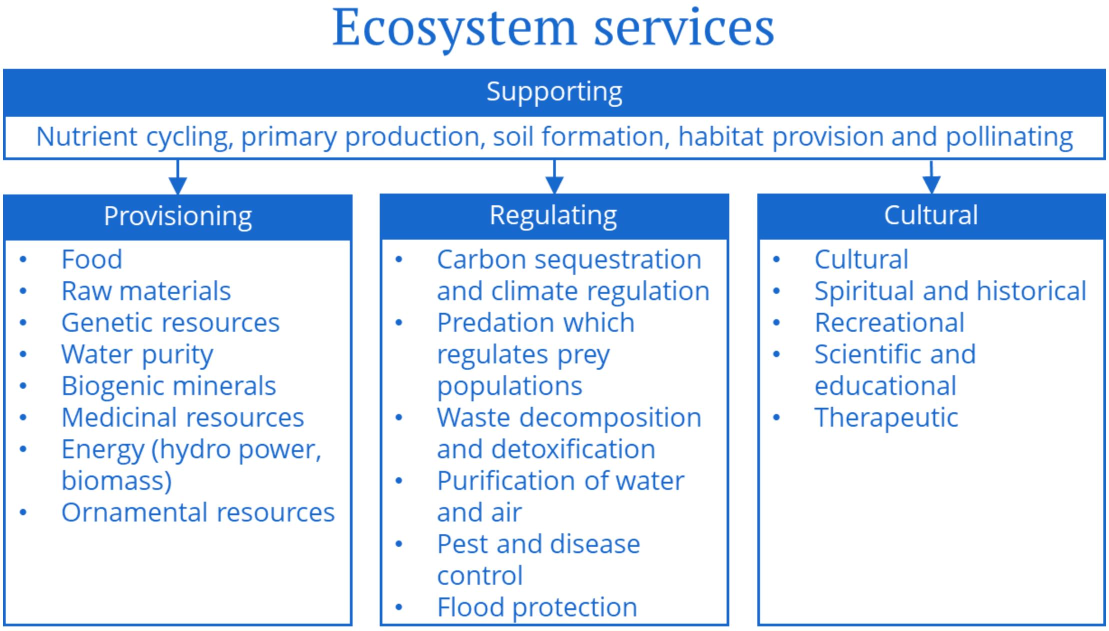


Figure 4 Overview of ecosystem services

As described in section 3.1, biodiversity can be directly affected by the presence of plastic litter in (marine) ecosystem. The cause-effect pathway for biodiversity is rather complex and large, since the loss of biodiversity (damage to ecosystems) is often the final effect of several cause-effect pathways. Climate change, photochemical ozone formation, terrestrial acidification, freshwater eutrophication, toxicity, water use and land use ultimately all cause damage to ecosystems, or more specifically the regulating services of ecosystems, and thereby biodiversity. The damage to human health caused by the loss of the provisioning, cultural and some of the regulating ecosystem services have not yet been included in our current impact assessment methods.

3 Qualitative assessment

Not all environmental impacts of the riverine plastic collection system can be quantified. Whenever this is the case, qualitative information will be used to assess the environmental situation in a literature of which the results are described in this chapter. As the geographic scope of the project is the Benelux and more specific the Rhine River in the Netherlands flowing into the North Sea just beyond Rotterdam, so is it the geographic scope of the qualitative assessment. In some cases, more general information is used whenever it was only available on larger scales.

3.1 Current environmental status

3.1.1 Environmental status of the water

Areas affected by plastic pollution

Due to the complex interplay of ocean currents and winds, plastic particles migrate throughout the oceans and shorelines, sometimes originating from locations thousands of kilometers away. As a consequence, plastic particles can be found all over the world: on land, in rivers, on shorelines and in oceans, at all depths. The land acts as an important source for the majority, around 80%, of plastic found in both rivers and oceans. On land, plastic from all sizes is transported by freshwater rivers to the saltwater seas and oceans. Once plastic litter enters the marine environment it can migrate throughout several compartments: coastlines, the upper ocean (i.e., floating), the water column (i.e., suspended), the ocean floor, and in biota (i.e., in flora and fauna). Whether a plastic particle floats or sinks depends largely on its density, which can range from 0.92 g/cm^3 for the floating low-density polyethylene to 1.30 g/cm^3 for the sinking polyethylene terephthalate, see Table 1. In general, a plastic particle with a density below 1 gram per cm^3 floats, while a plastic particle with a density below 1 sinks. However, different configurations of plastic particles can change this, e.g., polystyrene foam floats, while individual polystyrene particles sink. Other phenomena like fouling, aggregation and zooplankton uptake might cause a plastic to sink as well.[4] During the migration the larger macro plastic (> 5 cm) particles break down to meso (5 mm – 5 cm), micro (0.1 µm – 5 mm) or eventually nano (< 0.1 µm) sized plastic particles.[5–7]

However, the concentration of plastic particles does vary strongly across the oceans, resulting for example in the well-known Great Pacific garbage patch.[5] The Great Pacific Garbage Patch is estimated to be 1.6 million km^2, with an average particle density of 112 thousand particles per km^2.[8]

To get insights in the distribution of plastic in marine ecosystems both sampling as well as modelling are used. Due to sheer size of the oceans, plastic distribution prediction models give better insights in the distribution. These models show that plastic tends to have high concentrations where (1) a lot of plastic enters the marine system, e.g., South-East Asia, or (2) it accumulates in the so-called ocean gyres, like the Great Pacific Garbage Patch in the North Pacific Gyre, see Figure 5. Similar models have been made for plastic particles in the North Sea, demonstrating the transport distance of polystyrene and PET leached from rivers into the North Sea, see Figure 6.

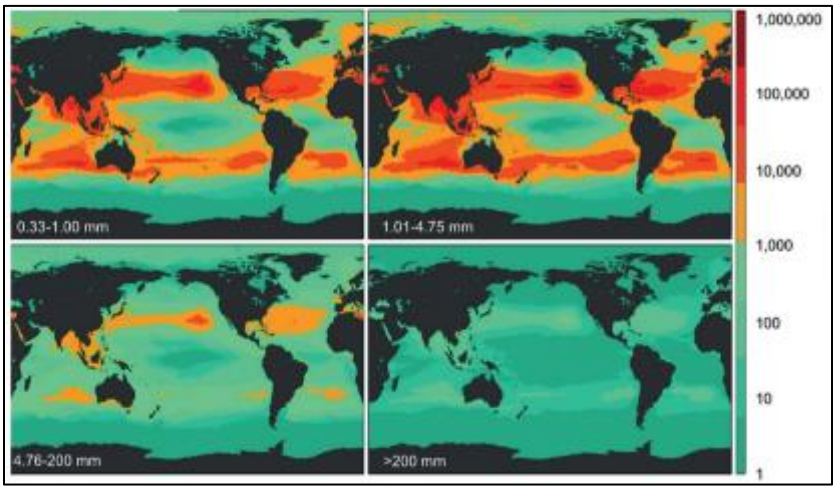


Figure 5 Model prediction of numerical plastic distribution per particle size range. Retrieved from UNEP, 2016.[5]

Plastic litter in the Rhine River

In the past years various studies focused on the presence of plastic litter in Rhine riverine system [9–12]. The difficulty with identifying the amount of plastic in the whole waterway is its heavy branching character, especially in the lower Rhine delta area in the Netherlands. As a consequence measurements of riverine plastic conducted upstream in Germany, might be not representative for the situation in Rotterdam [9]. Furthermore, the Rhine River slows down in this lower delta, due to its lower slope, possibly increasing sedimentation of particles in the river. It is suggested that this effect is particularly strong near Rotterdam where the Rhine is affected by the influx of brackish water and experiences tidal effect, however never proven. Sedimentation decreases the amount of floating and suspended plastic and increasing the amount of plastic in sediments.[9] This effect should be kept in mind when assessing the presence of plastic in the Rhine near Rotterdam, especially in relation to the cross-sectional location of the plastic in the river, e.g. floating, suspended or in the sediment. The analyses of sediment, excavated during installation of Catchy, showed the presence of plastic in the soil up to 3 meters deep. Field studies executed by Allseas demonstrated the additional tidal effect of having two opportunities to catch plastic, during the ebb outflow as well as the flood inflow of the sea water.

Due to the variability of measurement data along the Rhine, varying measurement techniques and varying types of plastic litter, i.e., macro, meso, micro and nano, studies on the presence of plastics in the Rhine are not comparable and therefore unable to identify a trend upon. A 2015 study by Van der Wal et al. (2015) estimated that the Rhine River contains around 3 million plastic particles, in the size range 300 µm to 25 mm, per km^2 river surface, resulting in hundreds of billions plastic particles being released into the North Sea annually. Of these particles the majority in number, 100-260 billion, are micro plastics with a size less than 5 mm. The remainder, 80-300 million particles, are small macro plastics with a size between 5 and 25 mm. The total amount of these small plastic particles being released from the Rhine into the North Sea is estimated to be 20 to 31 tons based on measurements in 2014, which would be around 33% of the annual North Sea plastic inflow.[5] Similar numbers were found during the Allseas sampling campaign in 2018 and 2019. For reference, the Po and Danube River transport significant larger amounts of plastic with around 120 and 500 tons annually, respectively.[13]

Mani et al. (2015) evaluated specifically the micro plastic particles along the whole stretch of the Rhine and found similar particle densities at some locations in the River as Van der Wal et al. (2015), however mostly upstream in Germany.[9,13] On the three test locations in Rotterdam significantly lower micro plastic particle densities were found by Mani et al. (2015) than on test locations upriver, in Germany, on average a factor 10 lower, corresponding to around 300 thousand plastic particles per km^2.[9]

Vriend et al. recently performed a rough study on the presence of floating macro plastics on the Rhine near Rotterdam and found a transport around 2 tons annually.[14] Vriend et al. compared their results to those obtained by Van der Wal et al. and observed significant lower macro plastic flows in their own study. A possible reason is the difference in the month the measurements were taken, indicating that the plastic flow has a strong variability through the year, caused by season variability in the river flow. It is thought that this variability between months can go as high as a factor 10 difference.[14] However, so far, no relation has been found between the presence of plastic and rainfall or tidal effects.[15]

Variation has been observed in the specific plastic recovered in all three studies, possibly due to the sampling techniques and seasonal changes, like precipitation, river discharge and human activity. Recurring plastics in all studies include polystyrene (PS), polyethylene (PE), polypropylene (PP), PET and PVC, which are also among the most produced plastics.[16]

As said, model predictions based on the hydrology Delft3D model[17] show the role of rivers in the presence of plastic in the North Sea, see Figure 6. In general, it is seen that the concentration of

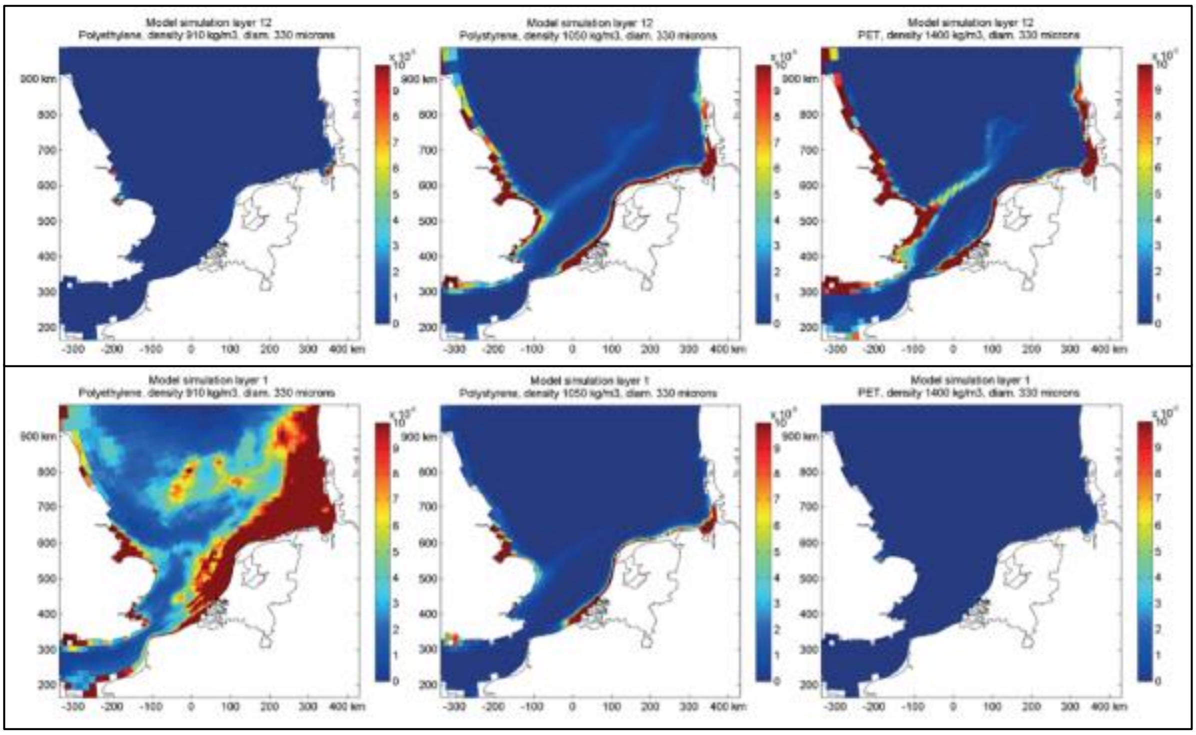


Figure 6 Plastic particle transportation model prediction for different plastics, PET and polyethylene with varying densities leached from rivers into the North Sea. Retrieved from UNEP (2016). The top graphs display the distribution in bottom water, the lower graphs display the distribution in surface waters.[5]

plastic particles is much higher around rivers mouths than elsewhere. However, the further transport of particles through the North Sea depends strongly on the specific plastic and its density.

Aquatic flora and fauna affected by plastic litter

Environmental impacts of plastic waste occur to the fauna predominantly in five ways:

- Entanglement
- Ingestion
- Chemical leaching and binding of toxins,
- Habitat loss, i.e., fauna destruction for example by the smothering of shores and seabed.
- Rafting

Entanglement is caused by the presence of macro plastics and therefore the most visible effect of plastic litter. Entanglement has been found throughout all marine taxa: mammals, e.g., whales, reptiles, e.g., turtles, birds and fish, see Figure 7. Entanglement often causes severe injuries or even death. Increased mortality rates, caused by entanglement have been found for seals and turtles and consequently associated with the threat of endangered species.[5,7]

Figure 7 Number of marine species with records of entanglement. Retrieved from UNEP (2016) [5]

Common sources of entanglement are abandoned fishing gear, e.g. buoys, traps, lines and nets, and plastic bags and utensils.[5,6] Especially since abandoned fishing gear is less common in rivers than in seas and oceans, entanglement is less frequent in riverine than marine environments and no significant observations of riverine entanglement has been documented. [6,7]

Ingestion can be caused by both macro and smaller sized plastic particles. Ingestion of plastic is found throughout most marine species, see Figure 8. However, especially seabird species seem to ingest large amounts. A possible reason for this large presence could be the transfer of plastic present in prey to predators. Once plastic is ingested it can cause several effects: starvation, reduced fitness, behavioral changes and reduced reproduction and thus mortality.[6,7,18]

Whether ingestion causes animal populations to decrease is unclear. However, since the evidence of the negative effects of ingestion on individual animals is crystal clear, this seems rather caused by lack of evidence than lack of actual effect population decrease.[5–7]

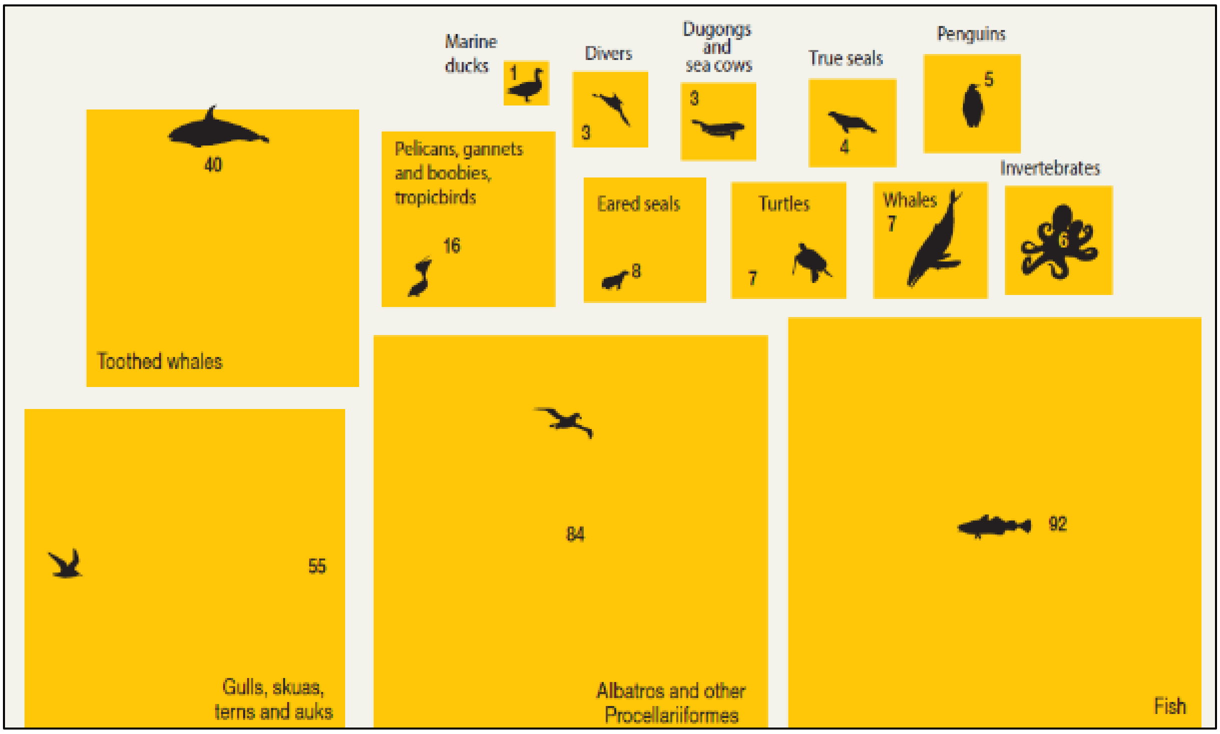


Figure 8 Number of marine species with records of ingestion. Retrieved from UNEP (2016) [5]

Despite the majority of plastic litter causing rather physiological damage through ingestion or entanglement than chemical and toxicological damage, these hazardous effects from plastic to biota should not be neglected. Several studies demonstrated leaching of toxins in marine environments and the negative effects on marine life.[19–21] However, there is no reason to assume such leaching does not occur in rivers or that riverine species are not affected by such toxins.[6]

Chemical additives are present in plastics to enhance certain characteristics of the materials, once the material degrades, these chemicals leach into the environment. There, the chemicals might become hazardous for those living in it.[22] The amount of toxic chemical additives present in the total marine plastic litter is estimated to be several million tons.[23] However, the leaching rate of these toxins is unknown. The leaching rate is strongly related to degradation rate of plastics, since toxins are released during degradation. A scientific review of the degradation rates of multiple plastics in various environments showed that the marine degradation rates can vary from 0 to 37 µm per year, resulting in degradation times of just a few years to several thousands of years.[22] Despite the large uncertainties associated with the leaching rates, it is important to acknowledge the potential impact of the toxins. However, due to the already existing large presence of toxins in oceans, animal populations unexposed to toxins do not exist.[5]

Toxins in plastic pollution are not always added during production as additives. Toxins present in oceans, be it from other, degraded plastic debris or another source, can also be attracted and absorb to plastic particles, through a process referred to as binding. Consequently, toxins can accumulate in the plastic debris. Once the plastic debris is ingested by animals, the accumulated toxins can be released and harm the animal.[24,25]

The effect of plastic litter and particles on fauna remains largely unknown. In a report on the effect of plastic litter, UNEP reported the damage to both coral reefs and mangroves, however, without further quantification. Coral reefs are mainly physically damaged through the movement of ropes and nets. Mangroves have the tendency to retain plastic and consequently become a plastic litter sink.[5] However, indirect ecosystem, and thereby habitat loss, can be caused by rafting. Rafting occurs when animals are carried by (plastic) debris from one ecosystem to another, in which they do not belong. Thereby damaging the destination habitat by introducing exotic and invasive species.[26]

Given the amount of available literature, research tends to focus on the marine rather than riverine flora and fauna. Nevertheless, there is no reason to expect that the five effects do not harm riverine flora and fauna in a similar way.

3.1.2 Environmental status of the air

Plastic is considered as a carbon intensive product, especially since the vast majority, 97% is fossil based, rather than bio based.[27] During the whole life cycle of fossil based plastics, greenhouse gasses are emitted, e.g. during the extraction of raw materials -oil and natural gas- and production of the plastic in the petrochemical industry. The greenhouse gasses end up in the atmosphere, contribute to the greenhouse effect, thereby global warming and eventually climate change. Plastic production is thus related to the environmental status of the air.

Carbon emissions during plastic production

The total carbon footprint of plastic was 1.7 Gt CO_2-eq in 2015 [28], roughly 3,4% of the global carbon footprint [29]. Not all plastics have the same carbon footprint. As said, common plastics in the Rhine River are polystyrene, polyethylene, polypropylene, PET and PVC. Other common plastics are acrylate and polycarbonate. Table 1 shows the carbon footprint of different plastic particles from the ecoinvent 3.5 database.[30] In general it is seen that the common plastics in the Rhine River are among the plastics with a slightly lower carbon footprint. On the other side, it is also seen that plastic with higher carbon footprints are often plastic that are more likely to sink than the plastic with lower carbon footprints and thereby harder to recover from both rivers and oceans.

Plastic	Abbreviation	Carbon footprint [30]	Relative gravity [4]	
Polypropylene	PP	2,12 CO_2-eq / kg PP	0.90 – 0.92	*Floaters*
Polyethylene, low density	LDPE	2,01 CO_2-eq / kg LDPE	0.92 – 0.93	
Polyethylene, high density	HDPE	2,09 CO_2-eq / kg HDPE	0.94	
Seawater Specific Gravity (1.025)				

Polystyrene	PS	3,76 CO_2-eq / kg PS	1.04 – 1.09	*Sinkers*
Poly methyl acrylate	PMMA	7,47 CO_2-eq / kg PMMA	1.14 – 1.20	
Polyvinylchloride	PVC	2,17 CO_2-eq / kg PVC	1.16 – 1.30	
Polycarbonate	PC	8,24 CO_2-eq / kg PC	1.19 – 1.25	
Polyethylene terephthalate	PET	3,17 CO_2-eq / kg PET	1.34 – 1.39	

Table 1 Carbon footprint and relative gravity of various plastics. Carbon footprints represent global market average plastics. Retrieved from ecoinvent 3.5 and evaluated with the "IPCC GWP 100a" method.[30] The specific gravity is the ratio between the density of one object, in this case plastic particles and another object, in this case water. Seawater has a slightly higher density than regular water. Retrieved from [4].

Airborne micro plastic pollution

Recent studies show that micro plastics cannot only be transported through water, but also through the air, the so-called airborne micro plastics. The airborne micro plastics can originate from various sources. Although one might expect the chemical and plastic producing industry as being one of these sources, research suggest that the industry has limited to no contribution to airborne micro plastics.[31,32]

3.1.3 Environmental status of the land

As said, most of the discarded plastic ends up in the oceans, transported by rivers.[5] Part of the plastic debris is flushed back onto the beaches and the coasts, there causing the damage to aquatic flora and fauna as described in section 3.1.1. Especially rafting is associated with plastic debris being flushed ashore, attracting biota, then being flushed back into the seas and transporting the biota to another ecosystem.[26] However, plastic litter might also be harmful further in-land. Some claim for example that plastic litter is also found is stomachs of terrestrial birds, as well as animals that feed on landfills, like birds and cows, especially at incorrectly managed sites, often in developing countries.[33–35]

Due to the strong focus of the scientific community on marine plastic pollution, rather than terrestrial plastic pollution, little evidence is available that supports the claims of the negative environmental impact of plastic on land, let alone the quantification of this impact. However, some claim that the impact of plastic on land might even be larger than in oceans.[36] It is suggested that plastic might affect flora and fauna through several mechanisms, which are often a combination of physical and chemical effects. Possible mechanisms include the high level physical and chemical effects on soils, ingestion by terrestrial and continental birds, reduction in growth of insects in soils, toxicological effects for fungi and mammals and the absorption of microplastics by plants, affecting their growth.[37,38] The increasing distribution of the microplastics over land, also poses an additional health risks to human beings. For example, by ingestion of plants that have absorbed microplastics. Despite the available knowledge on the possible mechanisms, more research is needed to be able to quantify the impacts.

3.2 Future environmental status

Within literature there is consensus that, without appropriate measures the amount of marine plastic litter will increase in the future. The main reason for the expected increase in litter is the expected exponential increase in plastic production, from 311 million tons in 2014 to 1800 million tons in 2050. Research predicts that, given the vast expected increase of plastic in our daily lives, with business as usual, the annual flux of plastic into aquatic systems will increase from roughly 20 million tons in 2016 to 90 million tons in 2030. Depending on how effective mitigation measurements will be in the future, same models predict that it is possible to limit the annual influx of plastic to 20 million tons annually. [5,7,23,39] With this expected increase in plastic, both on land as well as in the aquatic system, there is little doubt that the described current environmental status of all elements described in chapter 3.1 will worsen. However, the extent of the deterioration is not quantified and descriptions of the future status remain qualitative. The importance of further efforts to prevent plastic from entering the aquatic system and the removal of already present plastic litter is underlined by the fact that the most ambitious scenario, where the annual influx of plastic is mitigated to 20 million tons annually, is still considered 12 million tons too high. In global policy making, a common target is to bring the amount of plastic that enters the marine ecosystem should be below 8 million tons.[39]

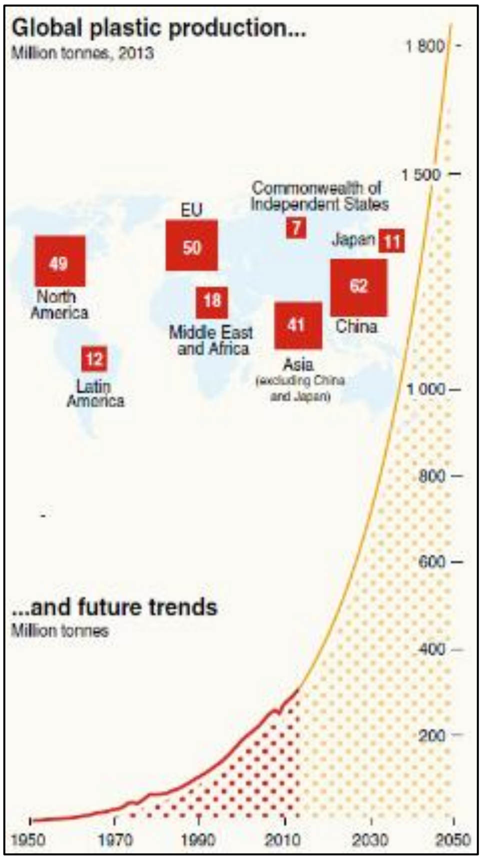


Figure 9 The current and future expected global plastic production. [7] Retrieved from [5].

3.3 Applicable regulations

A wide variety of both international, European and national conventions, protocols, agreements and laws are applicable when operating the riverine plastic collection system. The regulations can further be categorized in regulations that force prevention of unwanted activities, as well as protection of vulnerable flora and fauna. Since the geographical scope of this study is the Benelux and in particular the Netherlands, specific regulations for this geography are treated separately. International regulations are applicable more widely. The implications of the identified, relevant regulations are likely to be small, since the current location of the Vijfsluizerhaven is limited in wildlife, an industrial area and does, as far as known, not include vulnerable flora and fauna. Nevertheless, it is relevant to be aware of the regulations that are active, whenever the current situation or location might change.

Convention on the conservation of European wildlife and natural habitats

The Convention on the conservation of European wildlife and natural habitats, also known as the Bern convention, is an overarching convention signed by 51 European as well as African parties, promoting the protection of wildlife and habitats, and more specifically animals and plants. The convention distinguished three groups: Strictly protected flora species (plants), referred to as Appendix I, strictly protected fauna species (animals), referred to as Appendix II and protected fauna species, referred to as Appendix III. The Dutch ministry of Agriculture, Nature and Food maintains specific list for the three distinct appendices in the Netherlands [40]. The appendices include various aquatic plants and animals and therefore, extra attention should be paid to those species whenever operating near them.[41] As part of the Bern convention multiple separate convention have or already had been originating treating specifically animals or habitats.

3.3.1 International conventions on the protection of animals

Convention on the conservation of migratory species of wild animals

The Convention on the conservation of migratory species of wild animals, also known as the Bonn Convention or the CMS, forces its 131 parties, covering the majority of Europe, Africa and South America, to protect migrating species in order to prevent them from becoming extinct or endangered. The convention distinguished two groups of migratory species: those already endangered, referred to as Appendix I list, and those not endangered, Appendix II list. For the Netherlands those list are provided by the ministry of Agriculture, Nature and Food [42,43]. The list for the Netherlands contains several aquatic birds. In practice the convention requires extra attention to prevent harm to any of those species.[44]

The Birds directive

The Birds directive is one of the two main European Union environmental directives and deals with the protection of birds, both those species that reside throughout the year in Europe as well as migratory species that only stay for a shorter period in Europe. The directive is a response to the Bern convention and should be seen in the broader set of international habitat and animal protection regulations. The directive, just as the conventions, mainly deals with the birds to be protected (Annex I) and what is allowed related to hunting birds (Annex II-IV).

The Birds directive explicitly forbids the use of non-selective nets and traps for the hunt on birds. The national government can make exemptions from this provision and allow the use of nets and traps. The design of the riverine plastic collection system should thus secure that birds cannot be trapped in system.[45] Given that birds trapped in the cage, can always escape, there is no need to expect that any violations of the Birds directive. If necessary, an exemption (Dutch: “ontheffing”) for the operation of Catchy can be requested at the “omgevingsdienst Haaglanden” of the province of Zuid-Holland.[46]

Convention internationale pour la protection des oiseaux

The Convention internationale pour la protection des (English: International Treaty for the protection of birds) was signed in 1950, enforced from 1963 and focusses on the protection of wild birds during reproductive period and migratory birds during the months March to July and endangered birds or those of particular interest to science throughout the year. In practice it is important to note that this convention forbids the removal or relocation of any form of nests, eggs or birds during the breeding season, unless the species is explicitly excluded from the restriction by the province. Parties of the convention include the Benelux, as well as 12 other European countries.[47,48]

Agreement on the conservation of African-Eurasian migratory waterbirds

In line with the Convention internationale pour la protection des oiseaux and the Bonn convention, the specific protection of migratory water birds is documented in the Agreement on the conservation of African-Eurasian migratory waterbirds, also known as the AEWA. In the AEWA another list of 254 birds is composed, referred to as the Annex II list [49]. The AEWA is signed by almost 80 parties, including the European Union and its member states. As for previous regulations, in practice the AEWA requires extra attention around these birds.[50]

3.3.2 International conventions on the protection of habitats

Protocol on Water and Health to the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes

The Protocol on Water and Health to the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes, shortly also referred to as the Water Convention promotes its parties to protect international waters, like the Rhine River on both the national as international level, signed in 1999. The convention specifically mentions the importance of the protection of water ecosystems. The 43 parties of the convention, including the European Union (EU), commit, among others, to prevent sources of drink water and its related water ecosystems to be contaminated and to protect them from pollutions, for example from agriculture or industries and aim the eliminations of all substances that are “judged to be hazardous to human health and water ecosystems”. Furthermore, parties are promoted to form international bodies for specific transboundary waterbodies. For the Rhine River the Kommission zum Schutze des Rheins is such a body, which is a collaboration between Switzerland, Liechtenstein, Austria, France, Germany, the Netherlands, Luxembourg and the EU.[51,52]

Convention on Wetlands of International Importance especially as Waterfowl Habitat

The Convention on Wetlands of International Importance especially as Waterfowl Habitat, also known as Ramsar, named after the Iranian city it was signed in, protects more than 2000 specific habitats in its 171 states. The convention forces it member states to protect the so-called Ramsar sites by proper management and use. The Netherlands has 55 Ramsar sites, of which 5 in the lower Rhine delta: Grevelingen, Volkerak, Haringvliet, Hollands Diep and the Biesbosch [53]. In practice, this does not limit the ability for Catchy to operate in its current location, but is likely to limit the locations of future operations in the Rhine(-Meuse) delta.[54]

The Habitats directive

The habitats directive the second of the two main European Union environmental directives and deals with the protections of natural areas, in particular the Nature 2000 areas. The directive operates three lists of animal species to be protected: the Natura 2000 area species (Annex II), strict protection of other species (Annex IV) and protection from exploitation species (Annex V). [55]

As for hunting, similar is described for other animals than birds, e.g., mammals or fish, in the Habitats directive as in the Birds directive. This means that it is not allowed to use non-selective nets or traps for other animals than birds as well. Again, since animals trapped in the cage can always escape, there is no need to expect any violations of the Habitats directive.[55]

3.3.3 National and regional regulations

Environmental protection act

The Wet natuurbescherming (English: "environmental protection act") is the main national environmental regulation in the Netherlands for environmental protection and is aligned with the European and International regulations mentioned above. The act also acknowledges the importance of two European directives: The Birds directive and the Habitat directive of the European Union. Another acknowledge act is the Dutch fishery act.[56]

Fishery act

The Visserijwet (English: "fishery act") main purpose is the regulation of the fishing industry in the Netherlands, be it on seas, near coast or on lakes and rivers, which is likely not relevant for the riverine plastic collection system as such. However, the act also lists several provisions for the protection of fish in Dutch waters, most important the prohibition to hurt or kill fish, unless exemption is granted by the government. Without such exemption one should assure no harm to fish both during installation and operation of the system.[57] No violations of the Fishery act are expected.

Water act

The Waterwet (English: Water act) addresses a wide variety of water related topics, including the prevention of any pollutants from entering surface waters, formerly addressed in the Wet verontreining oppervlaktewateren (English: Surface water pollution act). The act consequently forbids the disposal of pollutants into the water without a license. Of course, this also prohibits the disposal of harmful plastic waste into the rivers but is also of particular interest for the operation of the riverine plastic collection system. Due to the act measures should be taken that the system does not leak any material, i.e., waste, polluting or harmful compounds, into the water. If necessary, exemption can be acquired from local authorities.[58] Since common practices, as currently applied to boats, are followed for Catchy, no violations of the Water act are expected.

The act also requires those who work in or near water to take every measure possible to prevent damage on the shore and bottom of waterways, as well as the prevention of the disposal of any pollutants. If, by accident, the shore or bottom is nevertheless damaged or if pollutants are disposed, administrators of the waterway should be notified as soon as possible.[58] In the case of Catchy, three spud piles have been installed into the bottom of the waterways with prior agreement of the administrators, Rijkswaterstaat.

Treaty regarding the protection of the Rhine

The Verdrag inzake de bescherming van de Rijn (English: Treaty regarding the protection of the Rhine) is the formalization of the multilateral commission to secure further protection of the Rhine river. The six parties in the treaty are those in which the Rhine flows: Netherlands, Germany, France, Luxembourg, Switzerland and the European Union. The commission has the aim to improve and preserve the ecosystem of the river and, among others, the prevention of pollution in it, including suspended and precipitated substances.[59]

3.3.4 Indirectly related regulations

Apart from the list of regulations that directly address the protection of flora and fauna, relevant when operating the riverine plastic collection system, a multitude of regulations are present indirectly related to the project. For example, regulations involving waste and pollution, or regulations focusing on the marine life, rather than riverine. These regulations are out of scope and therefore not summarized but listed in 0.

3.4 Overall qualitative assessment of Catchy

Given the significant environment issues caused by plastic pollution in marine biota and that most of this plastic enters the marine system through rivers, the collection of riverine plastic is undoubtably beneficial for both animals, their ecosystems and the wellbeing of the marine ecosystems. The riverine plastic collection system Catchy could play a valuable part in the prevention of plastic pollution. The main advantage of the reduced plastic inflow from rivers to oceans is the direct protection of animals and ecosystems. However, the literature study also shows that a quantification of the positive impact of collecting plastic remains uncertain, mainly due to the uncertainty about the proportion of the plastic in the river that is caught by the system. Only a portion of the riverine plastic is floating, while the remaining is suspended in the water column or even settled in the sediments of rivers.

The collection of suspended material is depending on its location in the river, i.e., being able to slip under the skirt or not. During the pilot operation of Catchy it was found that suspended materials like stones and glass were caught. Yet, Catchy's exact impact remains unclear. Another fraction of the plastic might also end up settling with sediments on the riverbed, which is not being collected by the system. However, the impacts on the sediment's ecosystem are unknown. So is it whether these settled plastics remain temporarily or permanently in the sediments.[9]

In case the collected plastic can be efficiently recycled, Catchy has a positive impact on the reduced need for virgin plastic as well. However, this is not thought to be the main advantage of the system.

Based on the literature research and consulted legislations, there is no reason to expect that the operation of Catchy itself is harmful for flora and fauna in its direct surroundings. Since the cage of Catchy is open and animals can therefore escape, no violations of the Birds and Habitats directive are expected. Being aware of the legal context nevertheless remains important.

4 Quantitative assessment

4.1 Assessment of the effects on the environment

4.1.1 Goal of the study

The goals of the quantitative environmental assessment are to:

1. Quantify the potential environmental impacts from Allseas' riverine plastic collection system "Catchy" throughout its life cycle.
2. Identify the environmental impacts of several environmental impact mitigation scenarios.

The results of the study are used to evaluate the design of the collection system within the LIFE Sustainable riverine PLastic removal and management (SouPLess) project requirements.

Each of the goals will be explained in more detail in the sections below. In the current project, a Life Cycle Assessment (LCA) for the riverine plastic collection system is performed. Within LCA the interactions of the studied system, in this case Catchy, with the environment are evaluated. This is done throughout the whole life: for the raw material extraction, production of materials and parts, transportation, use of the product and end-of-life. The interactions with the environment include both the resources extracted from the environmental and the emissions disposed into the environment.

By quantifying the environmental impacts of the system, this LCA study addresses key performance indicators (KPIs) developed in the LIFE SouPLess project.

The LCA identifies the so-called 'hotspots', i.e., the materials, processes and life cycle stages that have the highest contribution to the environmental impact of the product's whole life cycle. With the results obtained, mitigation scenarios are developed and evaluated to identify the mitigation potential of each scenario. With the results Allseas has an overview of improvement opportunities that can be seized to further improve the sustainable performance of the collection system.

4.1.2 Scope of the study

Product description

Catchy is a passive collection system and operated in the Vijfsluizerhaven, a harbor on the Nieuwe Maas, close to Rotterdam. Since the collection system is passive, it does not require any form of direct energy to operate.

The system, named "Catchy", comprises three elements: two floating booms, a floating frame and collection cage. The floating booms, 200 m and 12 m in length, guide waste under the effect of the wind and currents towards the collection cage. Both booms are equipped with an underwater skirt to catch both surface and submerged waste. The floating frame is secured to piles that allow it to move vertically with the tides, see Figure 10**Error! Reference source not found.**.

It supports a cage which is hoisted every month for emptying. The side walls of the collection cage are made of perforated steel plates, so that the water can go through while retaining litter up to the micro-size range. The system is fitted with elements that prevent the litter from escaping when the wind or the current direction change.

Figure 10 Overview of the Catchy collection deployed at the Vijfsluizerhaven (top), wide view of the location (left) and filled cage (right).

The collection system uses one 200-meter-long and one 12-meter-long boom that drive plastic towards a collection cage. Each boom consists of two parts, a floating arm and a 1-meter-deep underwater screen, made out of geotextile. The collection cage is secured to the bottom of the harbor using spud piles. There is little current in the Vijfsluizerhaven. It is thought that wind is the main determinant for the flow direction of the plastic, therefore the collection bucket and boom are positioned in such way to maximize the yield in case of the predominant wind direction.

The primary function of the collection system is to collect plastic litter up to 1 meter depth from the harbor. A secondary function is the collection of biomasses. The majority of the biomass is natural occurring biomass, like branches. The remaining biomass is processed wood. Other litter is collected occasionally in negligible quantities. In the study the plastic that is collected by Catchy is (mechanically) recycled. All biomass that is collected will be incinerated. At the end-of-life, Catch is disassembled and the separate parts go to different waste treatment facilities. In the default scenario as much of the materials as possible are being send to recycling. The landfilling waste disposal is not part of the default scenario but is evaluated in the sensitivity analysis.

Functional unit and reference flow

The functional unit describes qualitatively and quantitatively the function(s) provided by the products analyzed. The functional unit is a measure of the function of the products studied and it provides a reference to which all inputs and outputs can be related. This enables comparison of two or more different systems, e.g., Catchy versus Patje Plastic. For this study of the riverine plastic collection system the following functional unit was chosen:

> The collection of 120 kg riverine plastic, in dry weight, from the Vijfsluizerhaven in Rotterdam, the Netherlands, per year.

The 120 kg/year plastic yield is the current practical optimum. Along the course of the study the actual average yield was found to be closer to 84 kg/year.

The reference flow describes what is needed to fulfill the functional unit. For this study the reference flow is:

> One riverine plastic collection system "Catchy", with a total boom length of 212 meter.

The functional unit and reference flow were based on the performance of Catchy during its first three months of operation.

System boundaries

The collection system operates on the interface of two life cycles, see Figure 11:

- The use phase of the collection system itself.
- The end-of-life phase of the collected plastic litter.

The study focusses on the life cycle of the collection system, which is evaluated from cradle-to-grave. All life cycles stages: raw material extraction, production of the collection system, transport and installation, use and end-of-life are considered. The on-site optimization of the set-up is excluded from the system boundaries, since it is expected to have negligible environmental impact. The life cycle of the plastic that is being collected will (partly) be evaluated in section 4.1.6, the additional environmental information.

Allocation rules

In case of multi-functional processes, i.e., processes that have multiple outputs, mass-based allocation is used, whenever substantial amounts of by-products are produced. An example of a multi-functional process is the collection system itself, which "produces" both plastic and biomass as an output.

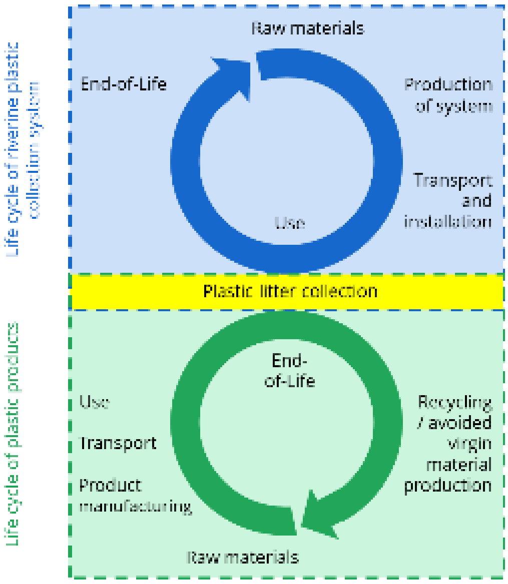


Figure 11 Overview of the interaction between the two life cycles of (I) the riverine plastic litter collection system and (II) the plastic litter itself.

For the end-of-life allocation, cut-off allocation is used. In this approach any environmental impacts (otherwise called environmental burden) arising from production and processing before a material becomes a waste are not 'attached' to the waste product. The underlying philosophy of this approach is that primary (first) production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. Consequently, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. For example, recycled paper only bears the impacts of wastepaper collection and the recycling process of turning wastepaper into recycled paper. It is free of any burdens of the forestry activities and processing required for the primary production of the paper[60]. The use of this approach was done based on a recommendation made by ecoinvent and in agreement with Allseas.

Impact assessment method, models and indicators

The impact assessment phase of an LCA is aimed at evaluating the significance of potential environmental impacts using the life cycle inventory (LCI) results. In general, this involves associating inventory data with specific environmental impact categories and category indicators.

Many life cycle impact assessment (LCIA) methods are available for a range of environmental topics. The ReCiPe 2016 (H) method is used for the impact assessment. ReCiPe is a renowned impact assessment and one of the most used amongst LCA practitioners.[61] The method calculates the potential environmental impact on 18 impact categories, shown in Table 2. See appendix Appendix B for the full description of the impact categories.

In addition, the ReCiPe 2016 method aggregates the results in three endpoint areas of protection: human health, ecosystem quality and resource depletion.

In the context of the LIFE SouPLess project multiple KPIs were identified, one of them focusing on energy consumption, therefore also the energy related impact categories from the Cumulative Energy Demand (CED) method will be included as well.[62] Due to the inclusion of the CED, it is not possible to aggregate the results into a single score.

Table 2 Impact categories selected from ReCiPe 2016 and Cumulative Energy Demand

Impact category	Abbr.	Unit	Method
Life Cycle Impact Assessment Indicators			
Climate change	GWP	kg CO_2-eq	ReCiPe 2016
Stratospheric ozone depletion	ODP	kg CFC-11-eq	
Ionizing radiation	IRP	kBq^{60}Co-eq	
Ozone formation, human health	HOFP	kg NO_x-eq	
Terrestrial eco-toxicity	TETP	kg 1,4-DBC-eq	
Freshwater eco-toxicity	FETP	kg 1,4-DBC-eq	
Marine eco-toxicity	METP	PAF.m3.day	
Human carcinogenic toxicity	HTPc	kg 1,4-DBC-eq	
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DBC-eq	
Land use	LOP	m^2a crop-eq	

Fossil resource scarcity	FFP	kg oil-eq	
Ozone formation, terrestrial ecosystems	EOFP	kg NO$_x$-eq	
Terrestrial acidification	TAP	kg SO$_2$-eq	
Freshwater eutrophication	FEP	kg P-eq	
Marine eutrophication	MEP	kg N-eq	
Fine particulate matter formation	PMFP	kg PM2.5-eq	
Mineral resource scarcity	SOP	kg CU-eq	
Water consumption	WCP	m^3	
Cumulative Energy Demand			
Non-renewable, fossil	n/a	MJ	Cumulative Energy Demand
Non-renewable, nuclear			
Non-renewable, biomass			
Renewable, biomass			
Renewable, wind, solar and geothermal			
Renewable, water			

To prevent the interested parties from being overwhelmed by results, only the relevant impact categories will be reported. Particularly relevant impact categories are climate change, freshwater and marine eco-toxicity, human (non-)carcinogenic toxicity, fossil resource scarcity and the cumulative energy demand categories, which address the key performance indicators (KPIs) in the LIFE SouPLess project. Other relevant impact categories will be identified based on an endpoint normalization approach, as described by Van Hoof et al.[63]

Assumptions

The following assumptions were made during modelling:

- For any transportation by road between suppliers, coaters, the harbor and Allseas, the fastest route is used to determine transportation distances.
- For any transportation over water between suppliers and the harbor, the shortest route is used to determine transportation distances.
- The weight of coating is excluded from the total weight during transportation.
- Leaching of coating or materials from Catchy into the water is excluded from the study.
- The yield of Catchy is 10 kg plastic litter per month, which is the current achieved yield, based on samples taken so far.
- The current lifetime of Catchy is, with proper maintenance, assumed to be 10 years. Alternative lifetimes are evaluated in section 4.1.5.
- The collected plastic is 100% mechanically recyclable.

4.1.3 Inventory and modelling

The foreground data for the raw materials and production life cycle phases contain the amount of material, material type and processing steps required to produce the individual parts of Catchy and was collected by Allseas at their suppliers. The foreground data of the use and end-of-life phase were based on estimates by Allseas. For the background data, ecoinvent 3.6 cut-off by classification was used.[30] See Figure 12 for the system boundaries and the foreground vs. background.

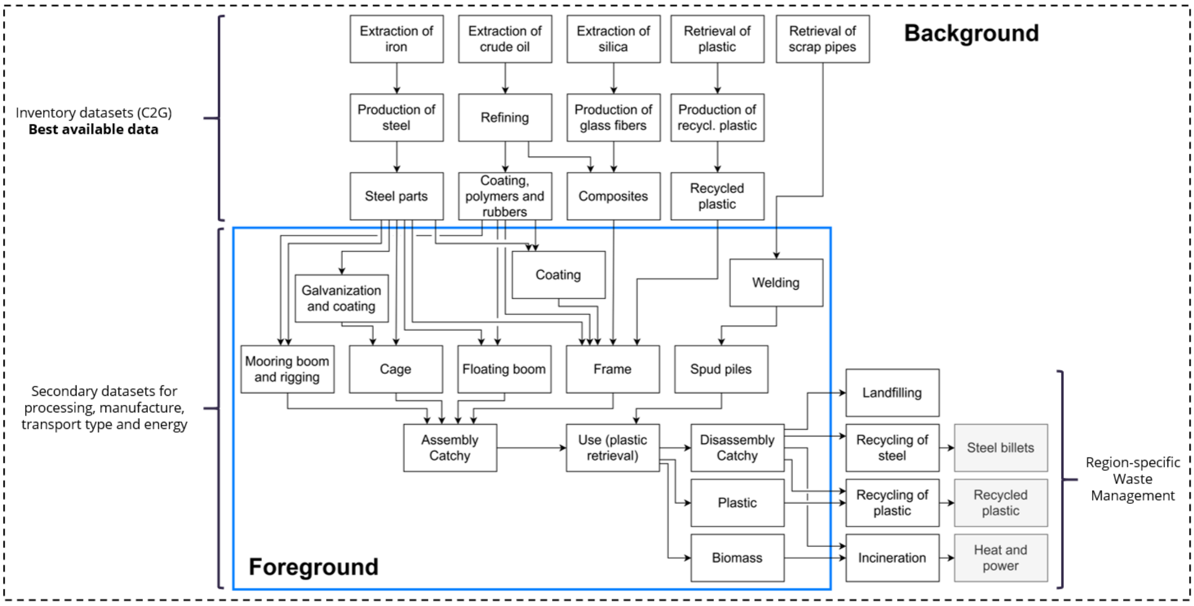


Figure 12 Overview of the system boundaries for the LCA of the riverine plastic litter collection system Catchy.

Catchy consists of six main elements: mooring boom, rigging, cage, floating boom, frame and spud piles, see Figure 12. The six main elements each consist of several parts, from different suppliers, made of different materials. For the six main elements the same, consistent modelling was applied, see Figure 13: Each material used by Allseas' suppliers was modelled first. The materials, together with the processing steps, were used as inputs for the specific parts that the suppliers made. The parts, together with the transportation, were used as inputs for the parts of the 6 main elements of Catchy, which make up the whole collection system. The modelling procedure is summarized in Figure 13.

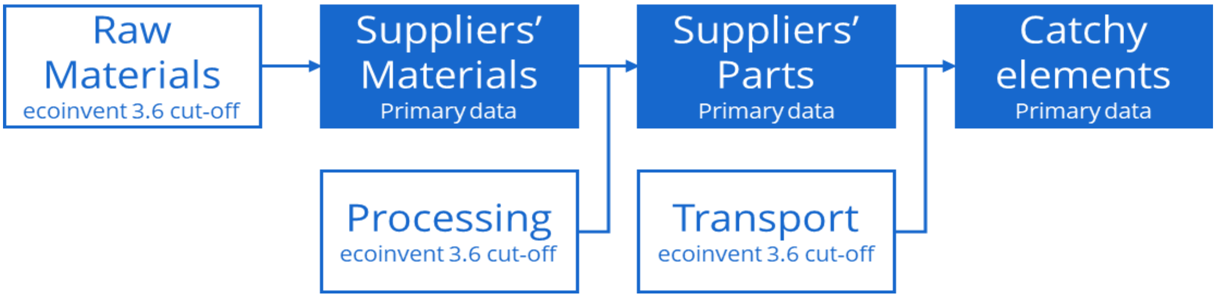


Figure 13 Procedure for modelling Catchy, starting at raw materials, through supplier's materials and parts.

The spud piles were made of scrap deep sea pipes. The spud piles were modelled to be burden free, consistently following the cut-off approach. This means that all the environmental burdens and benefits of the production of the pipes are part of their initial life cycle as deep-sea pipes. Consequently, these pipes are burden free in the life cycle of Catchy. Since this is specific for the case of Catchy, the use of burden free spud piles versus non-burden free piles is evaluated in the sensitivity analysis in section 4.1.5.

4.1.4 Results

Only the relevant impact categories are presented in the report. This was done by a combination of selection based on relevance in terms of the LIFE SouPLess project KPIs and the endpoint normalization approach, as mentioned in section 4.1.2. The graph showing the endpoint results for all impact categories can be found in appendix Appendix C. The relevant impact categories that will be further evaluated are shown in Table 3.

Table 3 Overview of the relevant impact categories and the origin of their relevance.

Impact category	Origin of relevance
Climate change	KPI in project *and* endpoint normalization
Freshwater ecotoxicity	KPI in project
Marine ecotoxicity	KPI in project
Human carcinogenic toxicity	KPI in project *and* endpoint normalization
Human non-carcinogenic toxicity	KPI in project *and* endpoint normalization
Fossil resource scarcity	KPI in project *and* endpoint normalization
Fine particulate matter formation	Endpoint normalization
Cumulative Energy Demand	KPI in project

The results in this chapter are presented in terms of relative contribution per life cycle stage. For the absolute figures on which the results are based, see Appendix F.

Results per life cycle phase

The environmental impacts of the whole life cycle of Catchy are presented in Figure 14. The results are normalized and grouped per life cycle:

- **Raw material extraction** of the materials for both the initial and spare parts.
- **Production** of the individual parts and Catchy as a whole.
- **Transportation** of the individual parts for production and during use and maintenance.
- **Use**, i.e., installation and maintenance. Maintenance includes the replacement of parts.
- **End-of-life**, i.e., the treatment required to dispose Catchy after its lifetime.

Figure 14 shows that the most impact comes from three life cycle phases: the extraction of raw materials; production of the parts for Catchy; and the use of the system. The impact for the two remaining life cycles, transportation and the end-of-life are less than 3% for the relevant impact categories.

For all impact categories, the majority of the environmental impact happens during either the raw materials extraction or production life cycle phase: during the raw materials extraction life cycle phase for **climate change** (43%), **fine particulate matter** (50%), **human carcinogenic toxicity** (46%), **fossil resource scarcity** (43%) and **cumulative energy demand** (40%); and during the production phase for **freshwater ecotoxicity** (51%), **marine ecotoxicity** (50%), and **human non-carcinogenic toxicity** (44%).

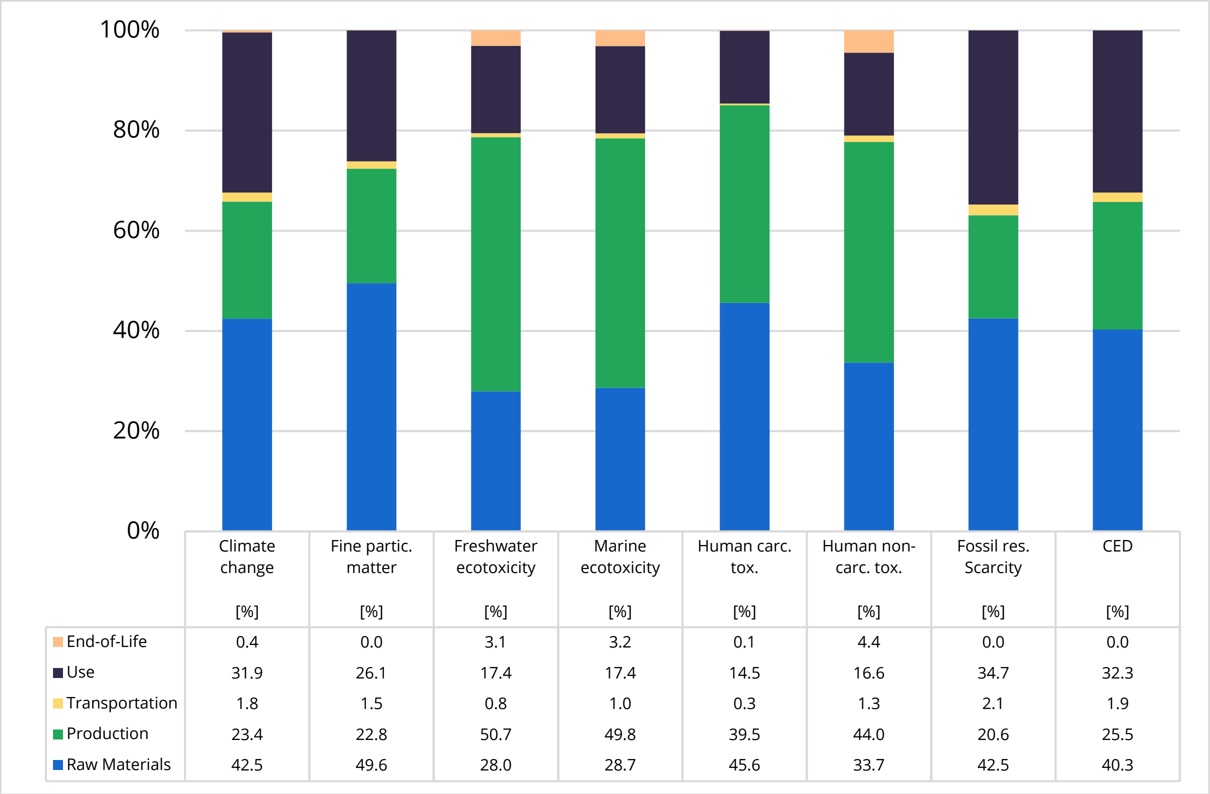
The impacts for the **raw materials extraction** life cycle phase are driven by the production of **unalloyed steel** (62% of the impact) used for the S235, S355 and unspecified steel types, **PVC** (12%) for the outer sleeve and **polystyrene foam** (11%) for the EPS60 blocks.

The impacts during the **production** life cycle phase are driven by the **metal working** (82%) for the initial set of metal parts, **welding** (5%) for the spud piles and **plastic processing** (4%) for the plastic parts.

The impacts during the **transportation** life cycle phase are driven using trucks for the transportation of **the cages for emptying** (51%), **scrap piles** (10%) and **baffles and cages for recoating** (8%) during the maintenance that happens every 5 years.

The impacts during the **use and maintenance** life cycle phase are driven by use of the **crane needed** (70%) to lift the cages for emptying, **metal working** (23%) needed to produce the replacement metal parts during maintenance and **plastic processing** (3%) for production of the replacement plastic parts.

The impacts during the **end-of-life** life cycle phase are driven by the treatment of **waste rubber** (65%) and **composite** (35%). The recycling processes for the remaining materials do not have an environmental impact. In the cut-off approach, see 4.1.2, the impacts for recycling are part of the life cycle in which the recycled materials are used.



	Climate change [%]	Fine partic. matter [%]	Freshwater ecotoxicity [%]	Marine ecotoxicity [%]	Human carc. tox. [%]	Human non-carc. tox. [%]	Fossil res. Scarcity [%]	CED [%]
End-of-Life	0.4	0.0	3.1	3.2	0.1	4.4	0.0	0.0
Use	31.9	26.1	17.4	17.4	14.5	16.6	34.7	32.3
Transportation	1.8	1.5	0.8	1.0	0.3	1.3	2.1	1.9
Production	23.4	22.8	50.7	49.8	39.5	44.0	20.6	25.5
Raw Materials	42.5	49.6	28.0	28.7	45.6	33.7	42.5	40.3

Figure 14 Relative characterized results for the most relevant impacts categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection, grouped per life cycle phase

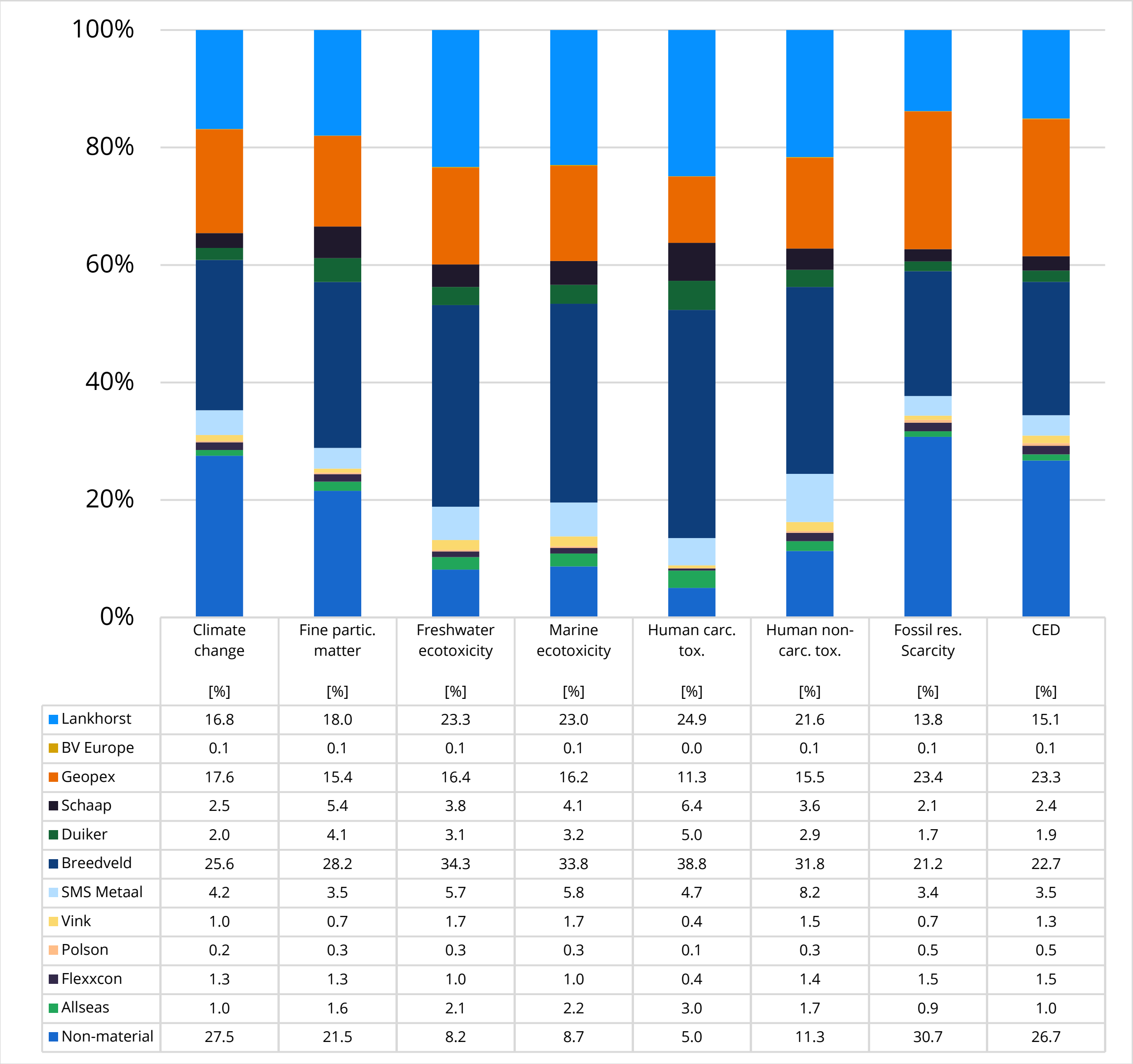
Results per supplier

Since both the raw material extraction and the production of the parts contribute to a significant share of the total environmental impact of Catchy, another grouping of the environmental impact results throughout the whole life cycle of Catchy is made. More detailed results on these life cycle phase can provide deeper insights and thereby relevant leverage points for future impact reduction, see Figure 15. The results are normalized and grouped per supplier. The full list of all materials supplied can be found in Appendix D.

Please note, that in this overview the replacement parts are grouped within their respective suppliers. These were earlier included in the "use" phase in Figure 14.

From the results it can be observed that the most impact comes from three suppliers: Lankhorst (supplier of the mooring booms and rigging), Geopex (supplier of the floating boom) and Breedveld (the majority of steel). The impact for the eight remaining suppliers is less than 7% for the relevant impact categories. Non-material impacts are for example the impacts from energy, transportation after assembly of Catchy and the use of equipment. The transportation of the parts from the supplier to Allseas is included in the environmental impact of the respective supplier.

Most impact is coming from Breedveld for **climate change** (26%), **fine particulate matter** (28%), **freshwater ecotoxicity** (34%), **marine ecotoxicity** (34%), **human carcinogenic toxicity** (39%) and **human non-carcinogenic toxicity** (32%); Geopex for **fossil resource scarcity** (23%) and **cumulative energy demand** (23%).

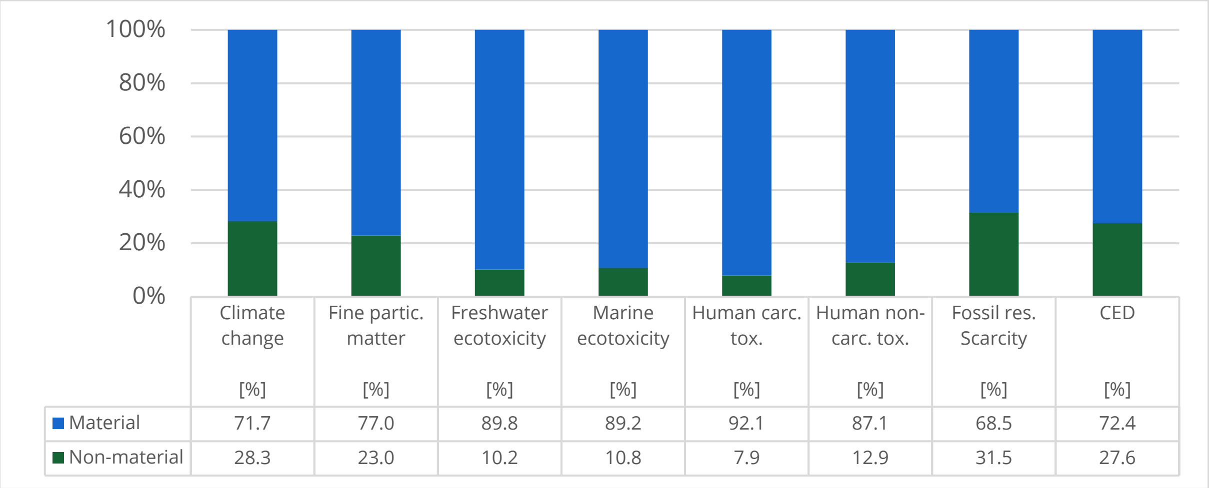


	Climate change [%]	Fine partic. matter [%]	Freshwater ecotoxicity [%]	Marine ecotoxicity [%]	Human carc. tox. [%]	Human non-carc. tox. [%]	Fossil res. Scarcity [%]	CED [%]
Lankhorst	16.8	18.0	23.3	23.0	24.9	21.6	13.8	15.1
BV Europe	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1
Geopex	17.6	15.4	16.4	16.2	11.3	15.5	23.4	23.3
Schaap	2.5	5.4	3.8	4.1	6.4	3.6	2.1	2.4
Duiker	2.0	4.1	3.1	3.2	5.0	2.9	1.7	1.9
Breedveld	25.6	28.2	34.3	33.8	38.8	31.8	21.2	22.7
SMS Metaal	4.2	3.5	5.7	5.8	4.7	8.2	3.4	3.5
Vink	1.0	0.7	1.7	1.7	0.4	1.5	0.7	1.3
Polson	0.2	0.3	0.3	0.3	0.1	0.3	0.5	0.5
Flexxcon	1.3	1.3	1.0	1.0	0.4	1.4	1.5	1.5
Allseas	1.0	1.6	2.1	2.2	3.0	1.7	0.9	1.0
Non-material	27.5	21.5	8.2	8.7	5.0	11.3	30.7	26.7

Figure 15 Relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection, grouped per supplier.

Results per material of the individual parts

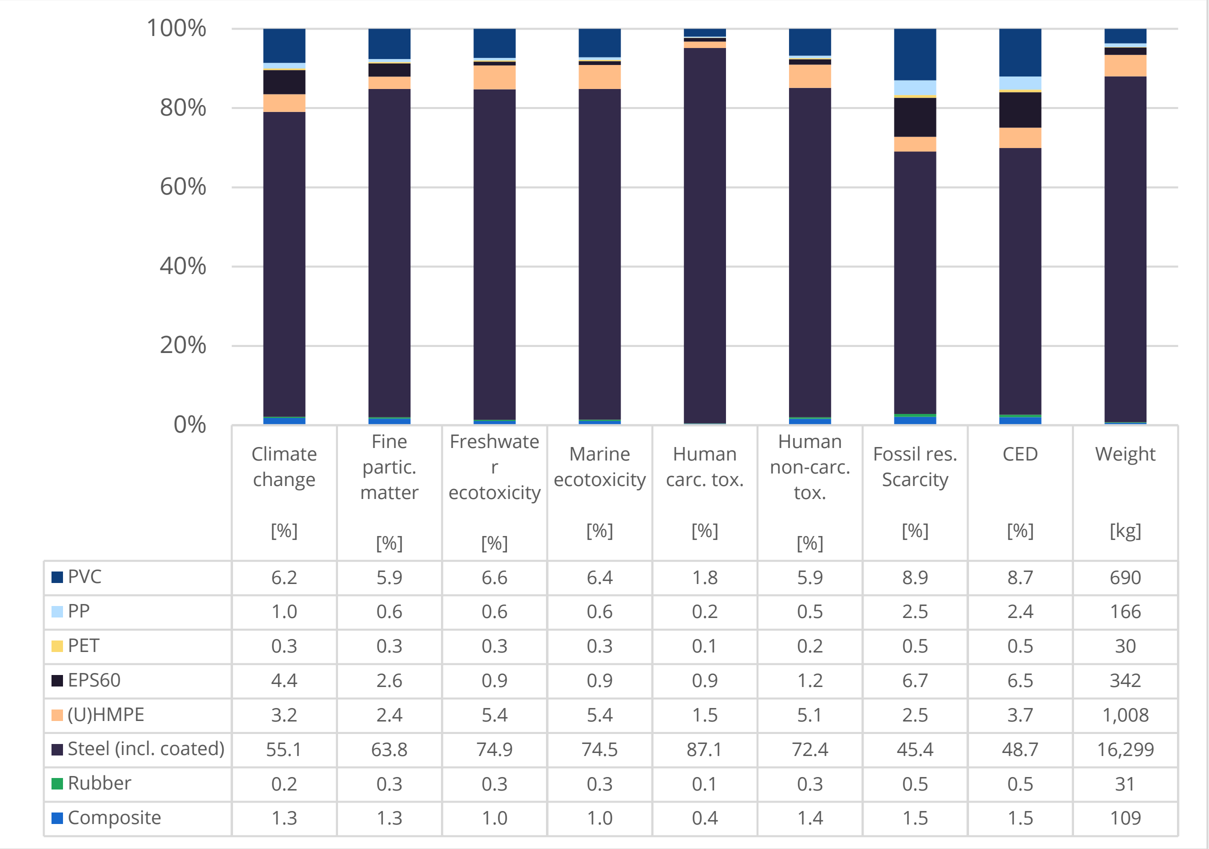
The total impact of Catchy can be, apart from per life cycle stage, split per material. Furthermore, a portion of the environmental impact of Catchy throughout its 10-year lifetime is associated with non-material processes, e.g., impacts that are associated to the use of the crane to lift the cages during the monthly emptying, welding during assembling Catchy or the transport throughout different moment of its lifetime. The split of the material and non-material impacts is shown in Figure 16. Most (over 69% across all impact categories) of the environmental impact is associated to the materials.



	Climate change [%]	Fine partic. matter [%]	Freshwater ecotoxicity [%]	Marine ecotoxicity [%]	Human carc. tox. [%]	Human non-carc. tox. [%]	Fossil res. Scarcity [%]	CED [%]
🟦 Material	71.7	77.0	89.8	89.2	92.1	87.1	68.5	72.4
🟩 Non-material	28.3	23.0	10.2	10.8	7.9	12.9	31.5	27.6

Figure 16 The division of the total impact of 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection, grouped per material and non-material impacts.

The second step is to look deeper into the materials that cause the environmental impact. Therefore, the material impact, is grouped per material, see Figure 17. For reference, the relative weight contribution of each material in Catchy is added as well.



	Climate change [%]	Fine partic. matter [%]	Freshwater ecotoxicity [%]	Marine ecotoxicity [%]	Human carc. tox. [%]	Human non-carc. tox. [%]	Fossil res. Scarcity [%]	CED [%]	Weight [kg]
🟦 PVC	6.2	5.9	6.6	6.4	1.8	5.9	8.9	8.7	690
🟦 PP	1.0	0.6	0.6	0.6	0.2	0.5	2.5	2.4	166
🟨 PET	0.3	0.3	0.3	0.3	0.1	0.2	0.5	0.5	30
⬛ EPS60	4.4	2.6	0.9	0.9	0.9	1.2	6.7	6.5	342
🟧 (U)HMPE	3.2	2.4	5.4	5.4	1.5	5.1	2.5	3.7	1,008
⬛ Steel (incl. coated)	55.1	63.8	74.9	74.5	87.1	72.4	45.4	48.7	16,299
🟩 Rubber	0.2	0.3	0.3	0.3	0.1	0.3	0.5	0.5	31
🟦 Composite	1.3	1.3	1.0	1.0	0.4	1.4	1.5	1.5	109

Figure 17 Relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection, grouped per material of individual parts. The last bar shows the relative weight contribution per material. Please note that the green bar, non-material impact, are not shown in still bar, since the is no mass to account it to.

From the results it can be observed that the most impact comes from the steel. The impact for each of the six remaining materials is less than 9% for the relevant impact categories. Most impact is coming from steel for **climate change** (53%), **fine particulate matter** (62%), **freshwater ecotoxicity** (70%), **marine ecotoxicity** (70%), **human carcinogenic toxicity** (84%), **human non-carcinogenic toxicity** (69%), **fossil resource scarcity** (44%) and **cumulative energy demand** (47%).

However, when these results are compared to the relative weight contribution per material, it can be observed that the relative impact from steel is lower than its relative weight for **all impact categories except human carcinogenic toxicity.** In this comparison the impact of EPS60, PVC and to a lesser extent PP are larger than to be expected based on their weight contribution.

4.1.5 Sensitivity analysis

Throughout the study several assumptions had to be made. To evaluate the sensitivity of the environmental impacts towards these assumptions a sensitivity analysis is done. A large sensitivity means that the change in the calculated environmental impact is large for a small change in the assumption. For the evaluation of the sensitivity of a continuous parameter, i.e. parameter that can have every value within a certain range, both a sensitivity coefficient, see Appendix G and the relative change are used to evaluate the sensitivity.[64] For non-continuous parameters, i.e. scenarios where a distinct different choice is made, only the relative change in the environmental impacts is used to assess the sensitivity.

The lifetime of Catchy

In this sensitivity analysis the lifetime of Catchy was evaluated. The current lifetime of Catchy is, with proper maintenance, assumed to be 10 years. The evaluated scenarios are a lifetime half (5 years) and twice (20 years) as long. The lifetime affects the time span over which the initial production impacts of Catchy can be spread and the amount of maintenance and use efforts that are required. This scenario will thus give insight in the ratio between the two. The results are normalized to the default scenario, i.e., these results are 100%.

From the results it can be observed that the change of the lifetime has a significant impact on the environmental impact. The conclusion is backed up by the determined sensitivity coefficients.

The impact of Catchy for a 5-year lifetime is significantly **smaller** and for Catchy with a 20-year lifetime significantly **larger** for **all impact categories**. From the graph is can be seen that the relative change is the least for **human carcinogenic toxicity**. The average coefficient was **0.45**. This indicates that, on average, the environmental impact will increase by 45% when the lifetime is increased by 100%, i.e., doubles. With an average sensitivity coefficient over 0.3, the lifetime is thus a sensitive parameter. The significant change of environmental impact when changing the lifetime is driven by the significant impacts coming from the use and maintenance of Catchy. The processes that contribute most to the impacts of maintenance are the **steel needed** for the replacement of parts, the **production of the steel parts** and the **PVC needed** for the replacement of parts, see Appendix E for the frequency of maintenance.

The findings are consistent with the relative contribution of the use and maintenance life cycle phases shown in Figure 15. Earlier it was found that the use and maintenance phase represent around 20% of the environmental impact on average. When the life time of Catchy is changed, it is only this life cycle phase that increase: in the case of 20 years, it doubles, having thereby a twice as high environmental impact as in the baseline scenario.

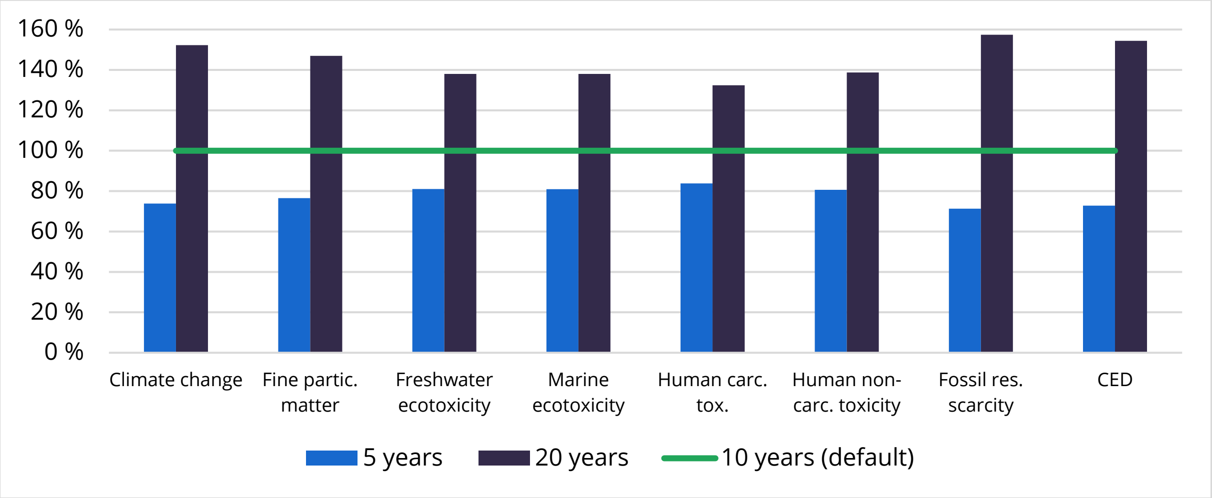


Figure 18 Comparison of the relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection, with a respective alterative lifetime of 5 and 20 years.

Non-burden free spud piles

In this sensitivity analysis the use of non-burden free piles was evaluated. In the current design of Catchy, scrap piles that were left at Allseas were used to secure Catchy into the bed of the harbor. However, it cannot always be expected that scrap piles can be used. Therefore, an alternative scenario, where the spud piles are not burden-free (explained in section 4.1.3) is evaluated, see Figure 19. The results are normalized to the default scenario, i.e., these results are 100%.

From the results it can be seen whether the piles are burden free or not, has a significant effect on the total environmental impact of Catchy for **all impact categories** and are thus a sensitive parameter. The relative change was especially large for **climate change** (+64%), **fine particulate**

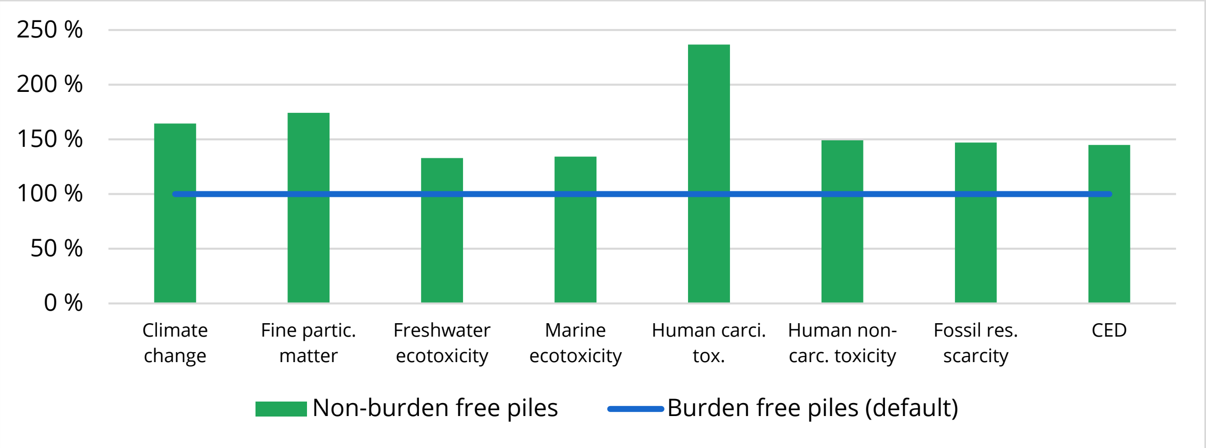


Figure 19 Comparison of the relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection with respective burden free piles and non-burden free piles.

matter (+74%) and **human carcinogenic toxicity** (+137%). For the other impact categories the increase was significant, but not as large: **freshwater ecotoxicity** (+33%), **marine ecotoxicity** (+34%), **human non-carcinogenic toxicity** (+49), **fossil resource scarcity** (+47%) and **cumulative energy demand** (+45%).

Modelling of steel materials

The initial results in section 4.1.4 showed that the majority of the (material) environmental impacts come from the steel parts. The production of the steel parts consists of two inputs: the material input and the manufacturing processing. Both inputs are evaluated in the sensitivity analysis. The results are normalized to the default scenario, i.e., these results are 100%.

In the initial model all unspecific steel types (s235 and s355) were modelled as unalloyed steel material inputs. However, some suppliers offer these steel types as low-alloyed as well. The modelling assumption was evaluated in an alternative scenario in which the unspecific steel was modelled as low-alloyed steel, see Figure 20.

From the results it can be seen that the effect on the final results had significant relative changes for **freshwater ecotoxicity** (+92%), **marine ecotoxicity** (+87%), **human carcinogenic toxicity** (+110%) and **human non-carcinogenic toxicity** (+47%). For the other impact categories the relative change was 5% or less. This indicates the modelling assumption is a sensitive parameter in the model, especially for the toxicity related impacts.

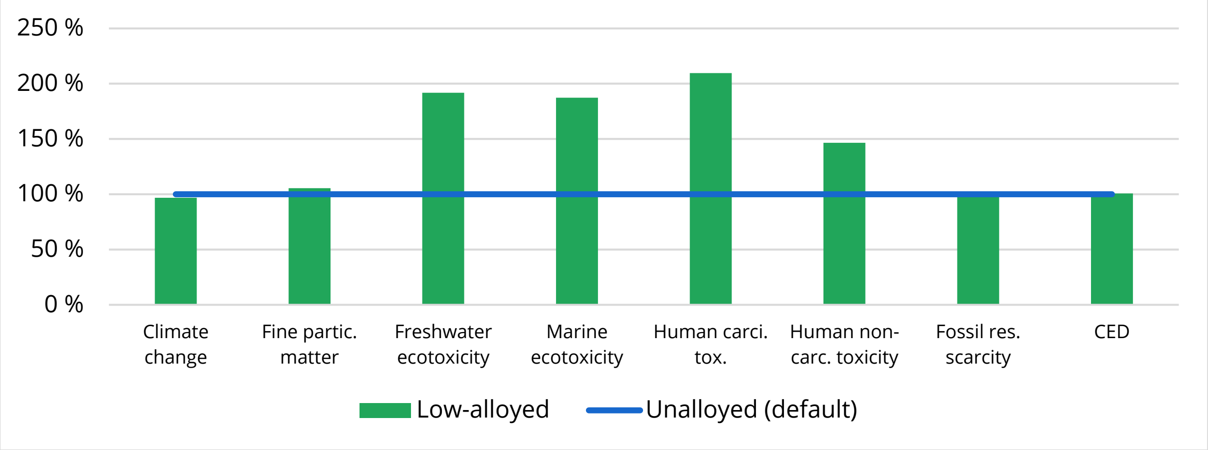


Figure 20 Comparison of the relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection with respective steel modelled as unalloyed and low-alloyed steel.

In the initial model the manufacturing processing was modelled as “metal working, average for steel product manufacturing”. The process describes an average technology of converting semi-manufactured product into final manufactured products, also considering potential material losses that happen during manufacturing. Given the large impact from steel parts and the general character of the process, it is relevant to evaluate its sensitivity. This was done by change the amount of processing needed from 1 kg processing per kg final product, to 0.5 kg processing per kg final product, see Figure 21. The change is purely hypothetical to be able to calculate a sensitivity coefficient.

From the results it can be observed that the change of the manufacturing process has a significant effect. However, the used change in the input parameter is, as said, purely hypothetical. To determine the sensitivity, the sensitivity coefficients are calculated, see equation (1).

An average sensitivity coefficient was found to be 0.37, with sensitivity coefficients over 0.5 for **freshwater ecotoxicity** (0.57) and **marine ecotoxicity** (0.55). The modelled manufacturing process is thus a sensitive input parameter. In practice this means thus that when the amount of processing needed per kg of raw material processed increases or decreases with 100%, the environmental impact will increase or decrease with 37% accordingly, on average across the impact categories.

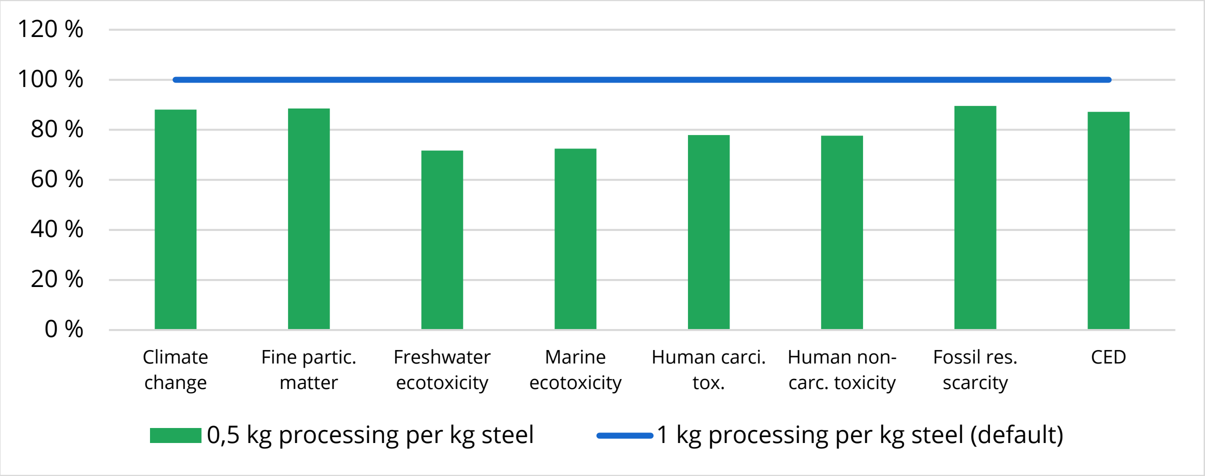


Figure 21 Comparison of the relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection with respective 1 kg and 0.5 kg processing per kg final product.

4.1.6 Uncertainty analysis

To evaluate the robustness of results in this study, we performed uncertainty analyses for the uncertainty present in the data, using the following procedure:

- Flows and parameters within the model were changed from deterministic to probabilistic values, i.e., from point estimates to probability distribution functions. As is common practice in LCA, lognormal distributions were used.
- For foreground data uncertainty, the pedigree matrix for the most relevant processes (i.e., maintenance processes and the inputs for the frame of catchy) was applied.
- For background data uncertainty, the uncertainty data provided by ecoinvent for the background processes was used. The ecoinvent uncertainty data are also based on pedigree matrix calculations.
- Monte Carlo simulations were carried out in SimaPro (10,000 runs). These evaluated the environmental impact for the whole life cycle of Catchy, excluding the avoided product.

The Monte Carlo analysis only evaluates the uncertainty in the data; the uncertainty in the impact assessment method or uncertainty due to methodological choices is not evaluated. The uncertainty is analyzed on the basis of reliability, completeness, temporal correlation, geographic correlation, and technological correlation – as defined in the Pedigree matrix.[65] The analysis was done for all impact categories studied (section 4.1.4). The 90% confidence intervals from the Monte Carlo analysis can be found in Figure 22.

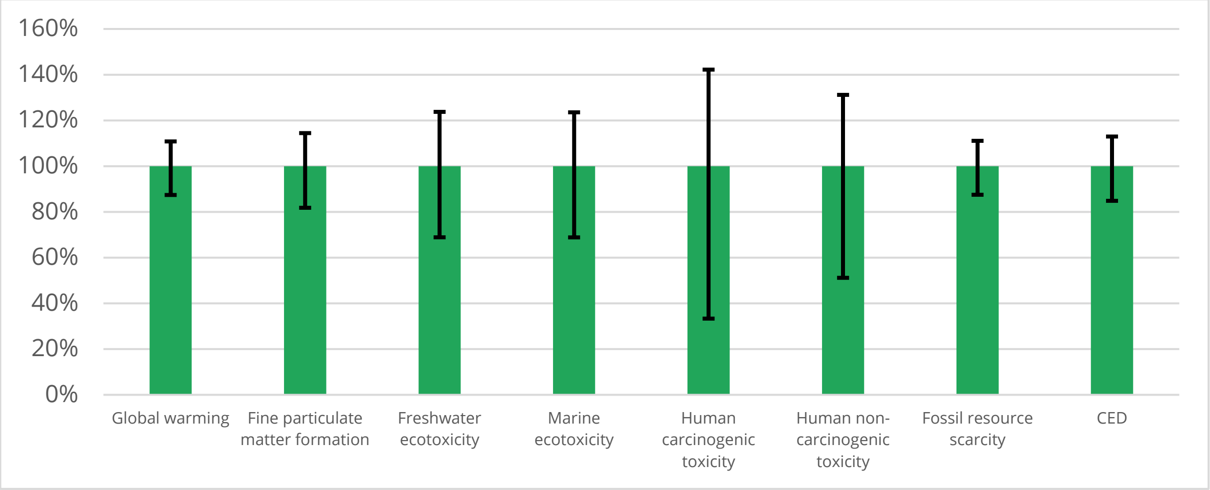


Figure 22 Relative error margins for a 90% confidence interval for the significant impact categories. The mean scores for each impact category have been normalized to 100%. The error bars thus indicate the relative error.

It can be seen that the data uncertainty for the toxicity related impact categories is large, especially for the human carcinogenic impact category. It is important to keep this large uncertainty in mind when assessing the results of the study. Due to the large amount of element contributing to toxicity related environmental impact, large uncertainties in the impact category are often seen. The data uncertainty in the remaining impact categories is considerably smaller.

4.2 Additional environmental information

Net environmental impact

Catchy collects plastic litter, which are assumed to be recycled into new materials. The production of virgin plastic can thus be avoided with the collected plastic. To evaluate the environmental benefits of the avoidance, the environmental impact of virgin plastic production can be subtracted from the environmental impact of Catchy, as so-called avoided products, see equation 2.

$$net\ impact_{Catchy} = impact_{production\ of\ Catchy} - impact_{production\ of\ avoided\ plastic} \tag{1}$$

Litter composition and treatment

The composition of the collected plastic is based on literature, see Figure 23 for the summary.[9] For the sake of simplicity, the density was assumed the be equal for all plastic in the conversion of reported volumes of litter to masses, necessary in the LCA model. The plastic was mechanically recycled in two consecutive steps: sorting of the collected plastic based on type and grinding of the plastic into flakes. The recycled plastic flakes are assumed to be of a similar quality as virgin plastic granulates.

After completion of the LCA model it was found that the litter collected by Catchy is likely to have a different composition than reported in literature and often contains higher shares of polyethylene and polypropylene. These are relatively low environmental impact plastics. The avoided environmental impact of the system might thus be lower in real life than reported in this study.

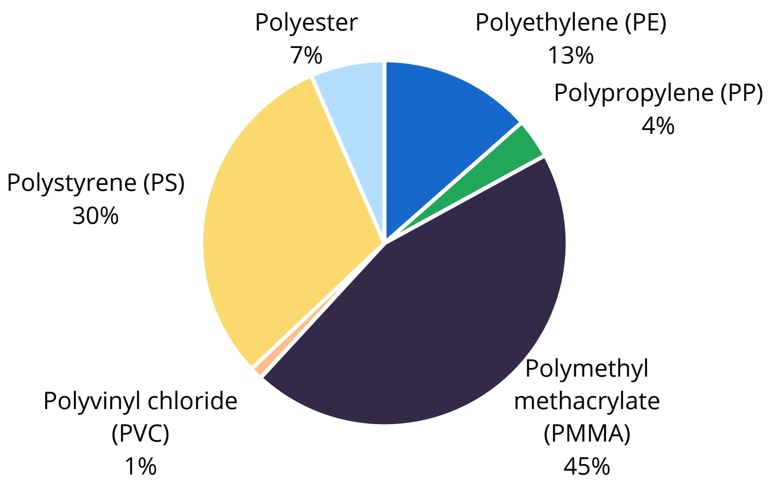


Figure 23 Summary of the plastic waste composition (on mass) as found in literature.[9]

The yield of Catchy is not just plastic but also biomass. Around 80%, in weight, of the total yield is biomass, of which around 45% is natural occurring biomass and around 25% processed wood. In the model all biomass is separated from the plastic and consequently incinerated as biowaste. In practice the separation of biomass from the plastic is done by hand as part of the pilot. However, in the future, Allseas aims to further industrialize this procedure. One option for this industrialization is mechanical recycling like it is modelled in the current study. Alternatives are chemical recycling or complete incineration with energy recovery. In these processes the collected litter, without further separation of biomass and plastic can be treated simultaneously. An initial screening did not show a significantly higher or lower environmental impact for complete incineration with energy recovery compared to mechanical recycling. In chemical recycling, the litter is introduced in a reactor in which its components are converted to raw materials.[66] Chemical recycling is rather novel and no life cycle inventory data was available for this study. Inclusion of chemical recycling and complete incineration with energy recovery as part of the disposal of the collected litter in the study is suggested for future updates of the results.

In the following sections the net environmental impact of Catchy, using equation (1) for different yields (0, 10 and 64 kg/month) and lifetimes (1, 10 and 20 years) are compared. The net impact of Catchy is also compared with an estimated net impact of Patje Plastic.

Plastic yield: comparison between current and theoretical maximum

The cut-off approach as used in section 4.1, in which the plastic collection yield was considered to be 0 kg/month, is taken as default in this section. The 10 kg/month plastic yield is the current practical optimum, in line with the functional unit. Along the course of the study the actual average yield was found to be closer to 7 kg/month. The 64 kg/month plastic yield is the theoretical maximum based on the size of the cage of the system. The results of the comparison are normalized to the default scenario of 0 kg/month plastic yield, i.e., these results are 100%, See Figure 24. These results are over the whole lifetime of Catchy throughout 10 years.

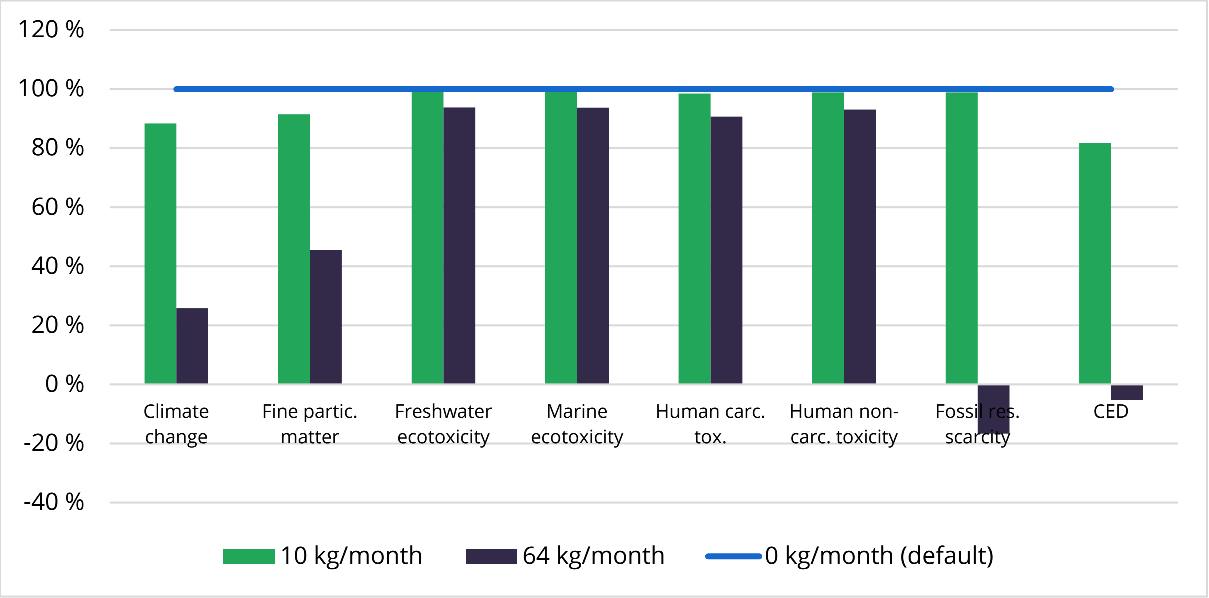


Figure 24 Comparison of the relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years with respective 0 kg, 10 kg and 64 kg collected plastic litter.

From the results it can be observed that avoidance of virgin plastic production, can significantly change the net result, especially when the maximum yield of 64 kg plastic litter per month could be achieved. The environmental impact does however not decrease for all impact categories equally. An increased plastic yield also includes extra efforts to separate and dispose the plastic and biomass, mainly increased energy consumption for the mechanical recycling and extra emissions from the incineration of the biomass. The environmental impact decreases significantly for the impact categories **climate change**, **fine particular matter**, **fossil resource scarcity** and **cumulative energy demand**. For the last two categories, Catchy's environmental impact would result in a negative score at maximum collection capacity of 64 kg plastic litter per month. A negative score indicates a net positive environmental impact of operating Catchy for plastic production, compared to producing virgin plastic. In practice it means that the environmental impact for fossil resource scarcity and cumulative energy demand for producing 64 kg virgin plastic per month is higher than operating Catchy one month, while it achieves a yield of 64 kg/month. The environmental impact decreases to a lesser extend for **freshwater ecotoxicity, marine ecotoxicity and human non-carcinogenic toxicity**. The environmental impact does not change significantly for **human carcinogenic toxicity**.

Plastic yield: comparison for different lifetimes and yield

For a more detailed evaluation of the hypothetical environmental impact reduction potential from the plastic litter collection, also the lifetime of Catchy is included. In this scenario only a yield of 10kg per month and 64kg per month is considered for lifetimes of 1, 10 and 20 years, see Figure 25.

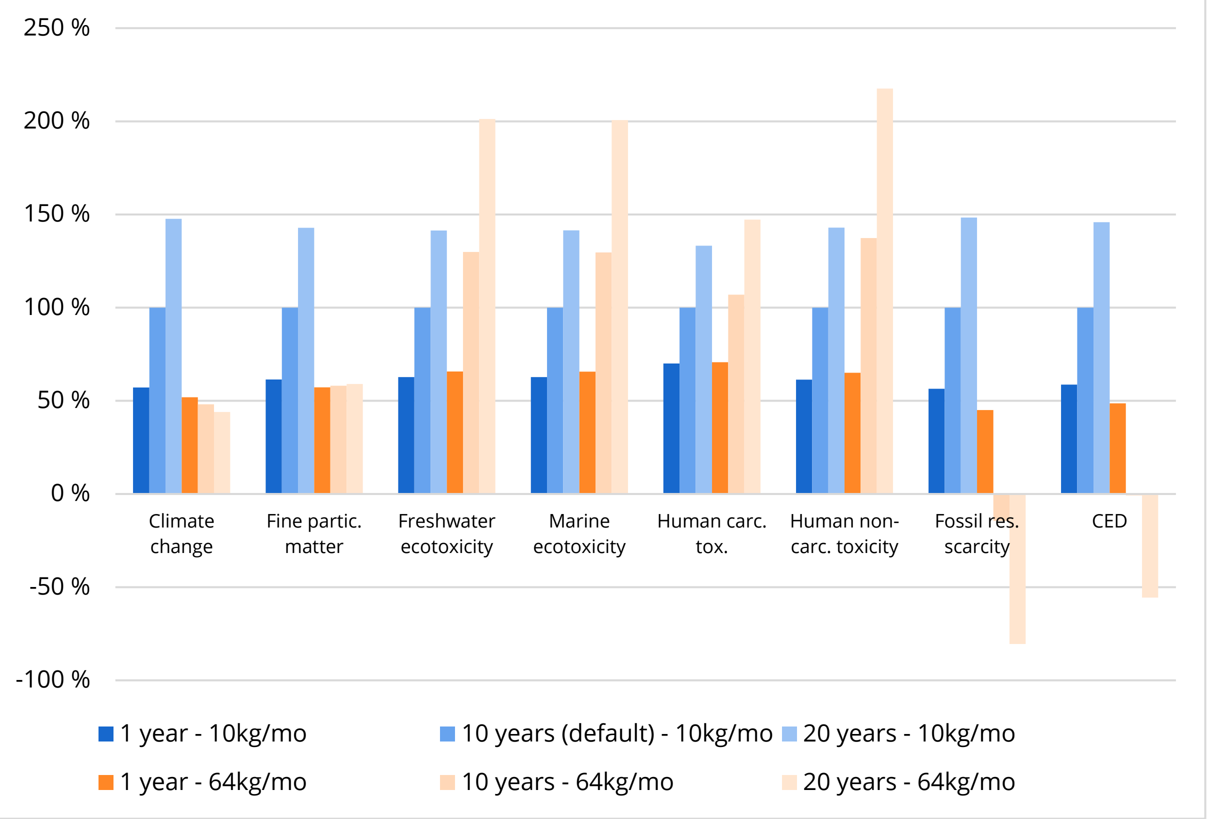


Figure 25 Comparison of the relative net characterized environmental impact for the relevant impact categories for 1 Catchy with respective 10 kg/month and 64 kg/month collected plastic litter, for 1 year, 10 years and 20 years lifetime.

From the results it can be observed that the lifetime has a significant influence in the overall environmental performance of Catchy. For a yield of 10kg collected plastic per month, it can be seen that the net environmental impact will increase for the longer lifetimes for **all impact categories**. This means that the environmental impact of the maintenance to keep Catchy operating is higher than the avoided environmental impact of virgin plastic production.

For a yield of 64 kg per month, it can be seen that the net environmental impact will decrease or remain stable for **climate change, fine particular matter, fossil resource scarcity** and **cumulative energy demand.** The net environmental impact will increase for the remaining impact categories.

By tweaking the input parameter for the yield and the lifetime, the optimum parameters at which the net environmental impact is zero can be determined. The optimalization was done for both the yield and lifetime individually, only for the climate change impact category.

To achieve a net-zero impact for climate change, with the current design of Catchy, a yield between 114 and 115kg per month should be achieved at a lifetime of 10 years. Alternatively, a lifetime between 125 and 126 years at a yield of 64kg also results in net-zero impact for climate change. Such a lifetime expectancy may not be realistic for Catchy. Also, the current model is likely to be inaccurate at a lifetime of over 100 years given the expected technological changes. These figures show that it is difficult for a system as Catchy to have a net positive or zero impact, only considering the quantitative results from the study and underlines the importance the inclusion of also the qualitative results as described in chapter 3. This comparison is made in the chapter 5, the Conclusions.

Other systems: comparison between Catchy and Patje Plastic

Catchy is part of the LIFE SouPLess project and not the only system that is developed. A second system has been developed and is deployed in the Antwerp harbor as well. A third system is currently under development. The developed model for Catchy is used to estimate the environmental impact of Patje Plastic. It is important to note that this is a generic estimate and rather describes Catchy with the size of Patje Plastic, rather than Patje Plastic specifically. Patje Plastic was modelled by changing the size of the core six elements and the maintenance required to match the set-up for Patje Plastic. The increase in weight is included in the transportation of the parts and the extra replacement parts needed. The input parameters are summarized in Table 4.

Table 4 Changes in input parameters for Catchy and Patje Plastic.

Element	Catchy	Patje absolute	Patje relative to Catchy
Cage	2 p	4 p	2x Catchy
Frame	1 p	2 p	2x Catchy
Rigging	2 p	3 p	1,5x Catchy
Floating boom	1 p	2 p	2x Catchy
Mooring boom – Long	1 p	4 p	4x Catchy
Mooring boom – small	1 p	0 p	0x Catchy
Spud piles	3 p	0 p	0x Catchy

Effective crane use for emptying cages	15 min	30 min	2x Catchy
Monthly plastic yield	10 kg	30 kg	3x Catchy
Plastic/biomass ratio litter	20/80	20/80	1x Catchy
Functional unit (kg plastic)	**120 kg**	**120 kg**	**1x Catchy**
Reference flow	**1**	**0.33**	**0.33x Catchy**

Since Patje Plastic is significantly larger than Catchy, Patje Plastic will have a higher environmental impact, when compared 1-on-1. For a fair comparison, following LCA theory, it is important to evaluate both systems while fulfilling the same functional unit: The collection of 120 kg of riverine plastic from the Vijfsluizerhaven in Rotterdam, the Netherlands, per year for 10 years. This means that the reference flow for Catchy remains 100% of its life cycle with a lifetime of 10 years. Patje Plastic, however, only *needs* 33% of its life cycle with a lifetime of 10 years to collect the *required* 120 kg. In the case the location only implies to composition of the plastic and not the yield.

The results of the comparison can be found in Figure 26. From the results we can see that in this initial comparison, the higher yield of Patje does outweigh the extra material needed to produce Patje Plastic, i.e., the net environmental impact of Patje Plastic to collect 120 kg plastic is lower than the net environmental impact of Catchy. This leads to the suggestion that increase in material use for the system to increase the yield, could potentially decrease the net environmental impact. Multiple effects drive these dynamics. Most important driver is the more efficient use of the crane during the emptying of the cages, since a large part of the time of the crane use is spent on its deployment rather than actual lifting of the cages. For Patje, which has 2 cages and this more actual emptying compared to the deployment, the use of the crane is thus more efficient. Also, the slightly higher yield to weight ratio (kg collected plastic/ kg collection system) for Patje Plastic (0.28 kg plastic/kg Catchy) compared to Catchy (0.26 kg plastic/kg Catchy) drives the lower net environmental impact.

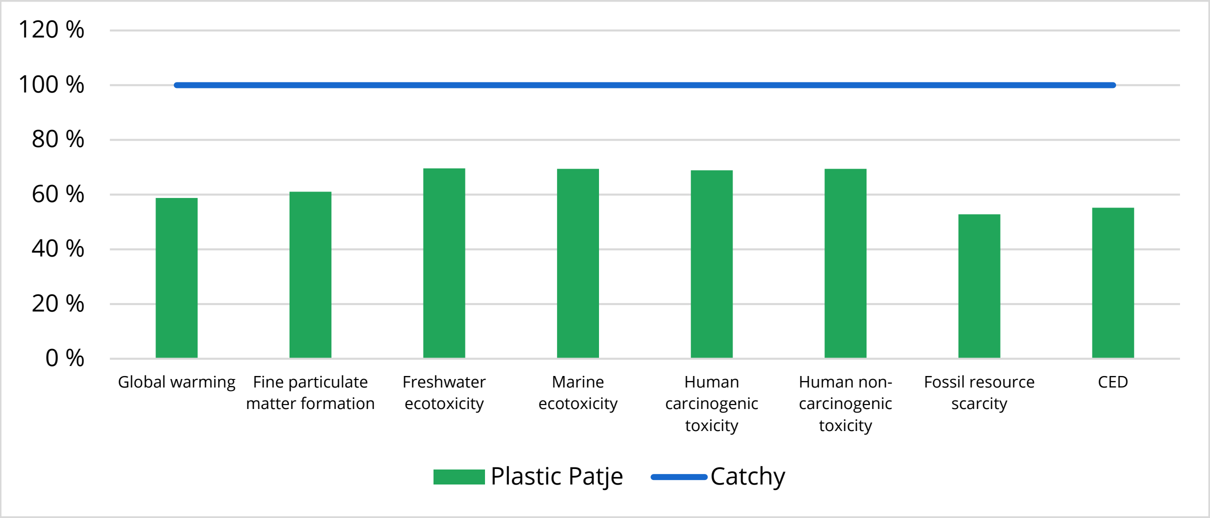


Figure 26 Comparison of the relative characterized results for the relevant impact categories for 1 Catchy throughout its lifetime of 10 years, including the avoided impact/benefits of the plastic collection (10 kg/mo), with 0.33 Patje Plastic throughout its lifetime of 10 years, including the avoided impact/benefits of the plastic collection (30 kg/mo).

4.3 Mitigation measures

The results in section 4.1.4 show that most of the environmental impact originates from two parts of the life cycle of Catchy: Steel used for the majority of the parts, and monthly use of the crane to lift the cages out of the system. To lower the environmental impact of Catchy, mitigation measures are likely to be most effective for these hotspots. In this section the possible reduction of environmental impacts is evaluated for three mitigation measures:

1. Reduce the amount of steel in the system and/or replace with a lower impact material
2. Use recycled steel instead of virgin steel.
3. Empty cages only when they are full.

Composting the recovered biomass as mitigation measure was evaluated as well. However, no significant reduction potential was found compared to incineration, see Appendix F for the figures– Impact assessment results

Fit for purpose: Reduce the amount of steel in the system

The large impact originating from steel is not necessarily due to the high environmental impact associated to steel as such, but also due to the shear amount of steel that is necessary for the system. A potential risk when designing a system like Catchy is overengineering, i.e., producing a system that is capable of more than strictly necessary for its purpose. Therefore, it is suggested to reevaluate the design of Catchy and focus on a design that is fit for its purpose.

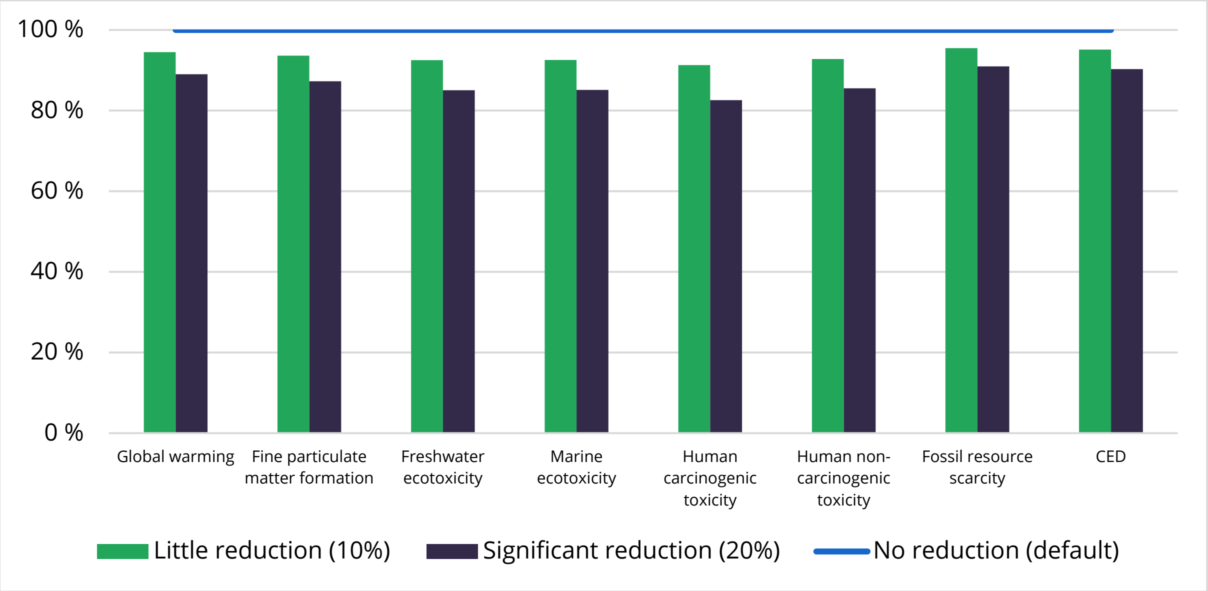


Figure 27 Reduction potential when reducing the steel weight by 10% or 20% for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection.

The mitigation potential of the steel reduction is evaluated for a 10% and 20% reduction, see Figure 27. A weight reduction of 10% results in a decrease of **at least 5% for all impact categories**. The impact decreases a little bit more for **fine particulate matter formation** (6%)**, freshwater ecotoxicity** (7%)**, marine ecotoxicity** (7%)**, human carcinogenic toxicity** (9%) **and human non-carcinogenic toxicity** (7%).

A weight reduction of 20% results in a decrease of **at least 9% for all impact categories**. The impact decreases a little bit more for **climate change** (11%), **fine particulate matter formation** (13%)**, freshwater ecotoxicity** (15%)**, marine ecotoxicity** (15%)**, human carcinogenic toxicity** (17%)**, human non-carcinogenic toxicity** (14%) **and cumulative energy demand** (10%).

Use recycled steel instead of virgin

Instead of reducing the amount of steel used, also the kind of steel that is used can be changed. In the current design the steel parts are made of 80% virgin/20% recycled steel. A way to reduce the environmental impact could be to use recycled steel instead.

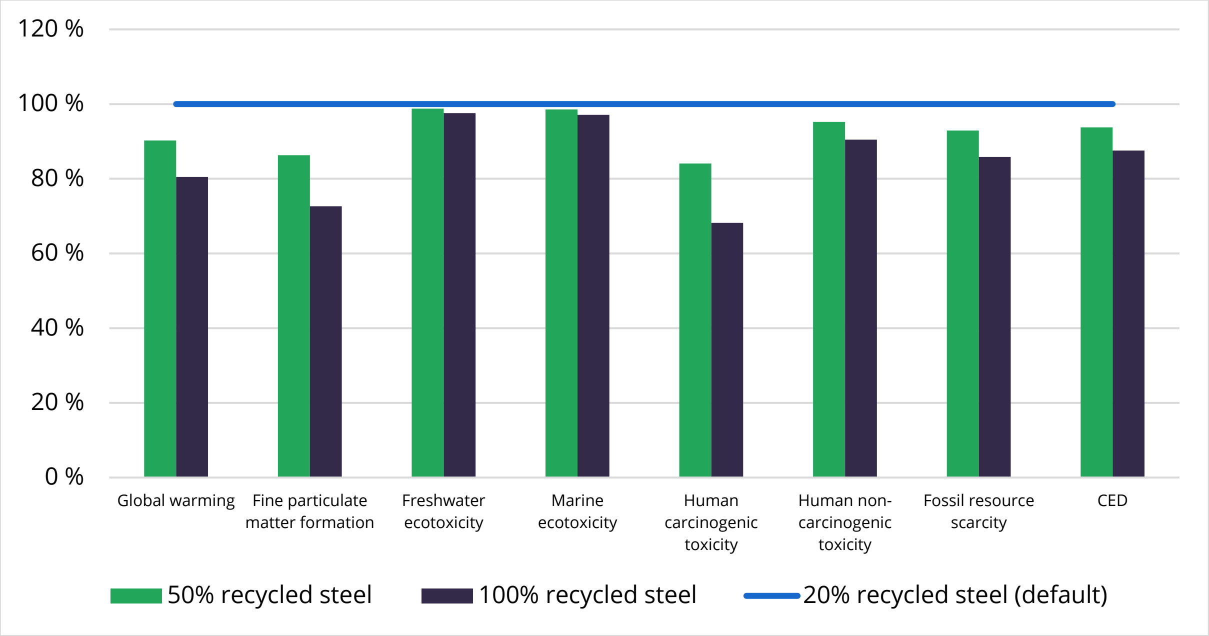


Figure 28 Mitigation potential when changing the steel input to 50% or 100% recycled content for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection.

The mitigation potential of the steel reduction is evaluated for a 50% and 100% reduction, see Figure 28. A recycled content rate of 50% results in a decrease for **all** categories. The impact will decrease most significantly for global warming, fine particulate matter and the human carcinogenic toxicity: **global warming** (-10%), **fine particular matter** (-14%), **freshwater ecotoxicity** (-1%), **marine ecotoxicity** (-1%), **human carcinogenic toxicity** (-16%), **human non-carcinogenic toxicity** (5%), **fossil resource scarcity** (7%) and **cumulative energy demand** (6%).

Similarly, a recycled content rate of 100% results in a decrease for **all** categories: **global warming** (-20%), **fine particular matter** (-27%), **freshwater ecotoxicity** (-2%), **marine ecotoxicity** (-3%), **human carcinogenic toxicity** (-32%), **human non-carcinogenic toxicity** (10%), **fossil resource scarcity** (14%) and **cumulative energy demand** (12%).

The significant decrease in impact for global warming, fine particulate matter and human carcinogenic toxicity is driven by the absence of particulate matter and (toxic) emissions of the scrap steel, used for recycling.

Empty cages only when they are full

Another big source of environmental impact is the monthly emptying of the cages. The impact of the emptying is driven by the use of the crane to lift the cages out of and into the system. Currently, the cages are emptied every month, regardless of their yield. The current yield modelled yield is around 10 kg per month. The actual yield is sometimes lower and has atheoretical maximum of 62 kg. The emptying of cages could thus be optimized by only emptying when they are full. This could lower the emptying frequency from 12 times a year to only 2 times a year, based on the yield of 10 kg per month, i.e., 120 kg a year (functional unit). The reduction potential of this mitigation measure is evaluated, see Figure 29.

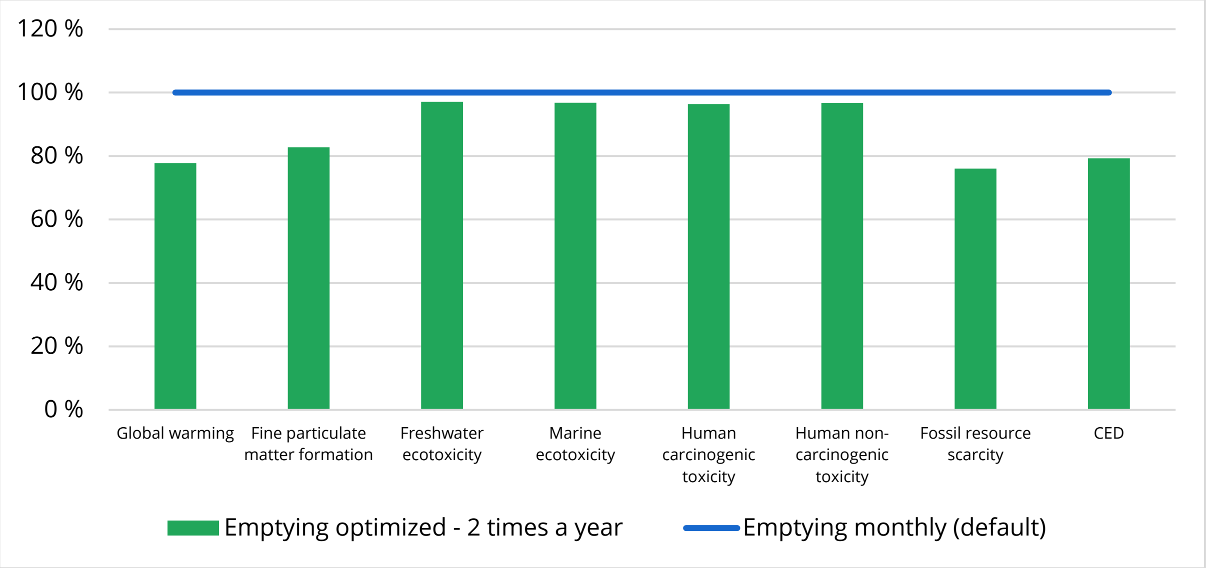


Figure 29 Mitigation potential when optimizing the emptying frequency of the cages from 12 times a year to 2 times a year for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection.

An optimization of the emptying that results in two instances per year results in a decrease for **all** categories, however the impact for **freshwater ecotoxicity** (-3%), **marine ecotoxicity** (-3%), **human carcinogenic toxicity** (-4%) and **human non-carcinogenic toxicity** (-3%) will decrease only slightly. The impact will decrease significantly for the remaining categories for the other impact categories: **global warming** (-22%), **fine particular matter** (-17%), **fossil resource scarcity** (-24%) and **cumulative energy demand** (-21%).

Combining measures: Fit for purpose, recycled steel and optimized emptying

The fit for purpose, recycled steel mitigation measures and emptying optimization independently have signification reduction potential. However, to emphasize the reduction potential of combined measures, a scenario in which the most effective measures of mitigation the mitigation options are combined is evaluated as well, see Figure 30. It is understood that implementing all the measures at the same time is difficult in practice. The scenario is rather to give insights into the maximum reduction potential and can put the different measures into perspective.

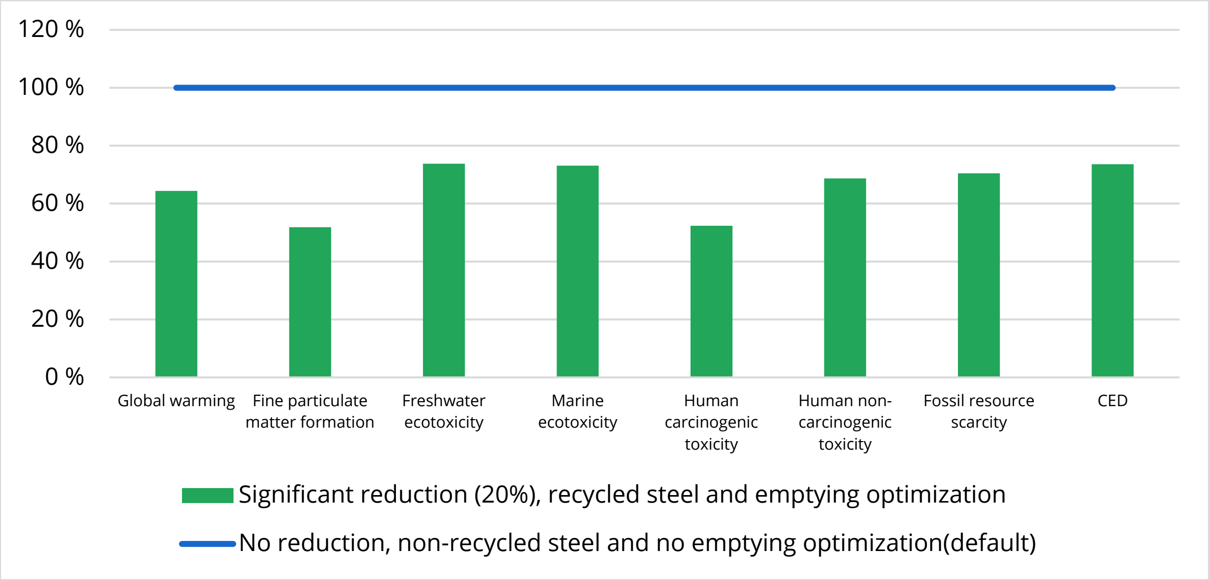


Figure 30 Mitigation potential when both reducing the amount of the steel by 20% and changing the steel input to 100% recycled content for 1 Catchy throughout its lifetime of 10 years, excluding the avoided impact/benefits of the plastic collection.

Combining all mitigation measures **at the same time** has a significant reduction potential for **all** impact categories: **global warming** (-36%), **fine particular matter** (-48%), **freshwater ecotoxicity** (-26%), **marine ecotoxicity** (-27%), **human carcinogenic toxicity** (-48%), **human non-carcinogenic toxicity** (-31%) **fossil resource scarcity** (-30%) and **cumulative energy demand** (-26%).

5 Conclusions

5.1 Environmental performance

Plastic litter and pollution undoubtedly cause harm to the environment, both in the water and on land. Also, the production of virgin plastics emits, among other pollutants, greenhouse gasses that accelerate global warming. The importance of plastic pollution, the overarching topic of this study, is undisputed.

For the qualitative study the following conclusions can be made:

- The Rhine river carries a significant amount of the plastic litter into the North Sea and thereby the aquatic ecosystem every year. The environment is harmed by this plastic litter through entanglement, rafting, ingestion, leaching of chemicals and toxins and fauna destruction.
- Collection of plastic litter from rivers with a riverine plastic litter collection system, like Catchy, would have a positive impact on the protection of flora and fauna. The extend of the positive impact remains unclear, since it is not known what share of the total plastic carried by the Rhine can be collected by the riverine plastic litter collection system.
- No legal issues are to be expected when operating the riverine plastic litter collection system.

For the quantitative study the following conclusions can be made:

- The main sources of environmental impact are:
    - The large amount of steel that is used in the system.
    - The monthly crane use for the emptying of the cages and maintenance of the system.
- The majority of the environmental impact during Catchy's life cycle happens during the raw materials, production and use phases.
    - The major sources of the environmental impact during the raw materials phase are unalloyed steel (62%), PVC (12%) and polystyrene foam (11%).
    - The major sources of the environmental impact during the production phase are metal working (82%), welding (5%) and plastic processing (4%).
    - The major sources of the environmental impact during the use phase are the crane use (70%), metal working (23%) and plastic processing (3%).
- The total impact of Catchy is largely dependent on:
    - The lifetime of Catchy
    - The possibility to use scrap pipes for the spud piles instead of virgin piles.
    - The use of unalloyed steel versus low-alloyed steel. The former being the best choice for the environmental.
- The net environmental impact of Catchy, by including the avoided production of virgin plastic, is significantly lower than gross environmental impact. For the theoretical maximum yield (64 kg plastic yield per month) the net impact can even be negative for fossil resource scarcity and cumulative energy demand.
- Only for high yields (>10 kg per month), the environmental impact from the maintenance of Catchy is lower than the avoided environmental impact from the plastic recovery.

Therefore, long lifetimes (with accompanying amounts of maintenance) are only environmentally beneficial for high yields.
- Patje Plastic has a lower environmental impact than Catchy when evaluating the same functional unit of the collection of 120 kg of riverine plastic from the Vijfsluizerhaven in Rotterdam, the Netherlands, per year for 10 years.

When considering the results from the quantitative study separately from the qualitative ones, it cannot be concluded unambiguously that Catchy is environmentally beneficial. For the current yield, the avoided environmental impact from virgin plastic production is lower than the environmental impact from Catchy. In other words, Catchy does have a net environmental impact. However, when including also the added environmental benefits identified in the qualitative study, Catchy delivers a positive contribution to the environment. The quantitative study also stressed the importance of either decreasing use of steel or crane use, or increasing the yield to have a net zero impact for at least the fossil resource scarcity and cumulative energy demand impact category, and potentially also climate change and fine particulate matter.

5.2 Limitations

Although a lot of effort was put in modelling Catchy as complete and robust as possible, there were assumptions or simplifications that could have an influence on the results. For example, the leaching of chemicals by Catchy into the environment are excluded. Also, better data sources are required for the manufacture of the individual parts made by suppliers, as currently generic data is used. For that reason, the results of this study should be used with caution.

Since the LIFE SouPLess project is ongoing, the practices considered in this study might not always reflect the most current practice. A clear example of practices that might get outdated during the project is the treatment of the collected litter. In this study it was assumed that the plastic mechanically recycled, while the biomass is incinerated. However, it is to be expected that current practices might be replaced in the future by chemical recycling of the plastic and biomass.

The model delivered in this study is a good first step to understand and get acquainted with the impacts of Catchy. In the future, the model could be fine-tuned and expanded to include information as close as reality, for example for the treatment of the collected litter.

5.3 Improvement opportunities

Based on the results of this study we recommend to:

- Evaluate the feasibility of the proposed mitigation measures, in order of highest potential impact reduction:
    1. Optimizing the emptying of cages. Since the crane use has been identified as the main source of environmental impact.
    2. Fit for purpose: reduce the amount of steel. Since the use of steel has been identified as another significant source of environmental impact.
    3. Use of recycled steel instead of virgin steel. Since the use of steel has been identified as another significant source of environmental impact.
- Evaluate the feasibility of increasing the yield for Catchy. Since it will have a positive effect on both the environment in qualitative and quantitative terms and might eventually even result in a net-zero environmental impact for some of the impact categories.

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Appendices

Overview

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– Indirectly related regulations

Appendix B – Full description of impact categories

Appendix C – The relevant impact category selection

Appendix F – Impact assessment results

Appendix G – Sensitivity coefficient

Appendix H – Sensitivity analysis of end-of-life scenarios

Appendix I– Pedigree matrix

Appendix A – Indirectly related regulations

Marine and other non-riverine habitats

- Water framework directive [67]
- Marine strategy framework directive [68]
- Convention for the protection of the marine environment of the North-East Atlantic [69]
- Benelux-Overeenkomst op het gebied van natuurbehoud en landschapsbescherming

Flora and fauna

- Convention on conduct of fishing operations in the North Atlantic [70]
- Overeenkomst inzake de bescherming van zeehonden in de Waddenzee [71]
- Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas [72]
- Convention on Fishing and Conservation of the Living Resources of the High Seas [73]

Waste and pollution

- Waste framework directive [74]
- Industrial emissions framework directive [75]
- Convention on the prevention of marine pollution by dumping of wastes and other matter [76]
- Stockholm Convention on Persistent Organic Pollutants [77]
- International Convention for the Prevention of Pollution from Ships [78]

Appendix B – Full description of impact categories

Table 5 Description of all impact categories considered in the study

Impact category	Description
Climate change	Climate change describes changes in the global, average surface-air temperature and subsequent change of various climate parameters. This effects things such as storm frequency and intensity, rainfall intensity and frequency of flooding. Climate change is caused by the greenhouse effect which is induced by emission of greenhouse gases into the air.[1]
Ozone depletion	Ozone depletion refers both to the general progressive loss of ozone in the stratosphere, which has been occurring for the past three decades, and on a more localised scale the loss of ozone taking place over the polar regions at a greater rate, but on a seasonal basis.[1]
Human toxicity, cancer effects	Human toxicity, cancer effects describes the degree to which chemical substances elicit a deleterious or adverse effect (cancer) upon the biological system of a human exposed to the substance over a designated time period.
Human toxicity, non-cancer effects	Human toxicity, non-cancer effects describes the degree to which chemical substances elicit a deleterious or adverse effect (other than cancer) upon the biological system of a human exposed to the substance over a designated time period.
Particulate matter	Particulate matter is made up of a number of components, including acids, organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential for causing health problems. Particles that are 10 micrometers in diameter or smaller can pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.
Ionizing radiation	Ionizing radiation has enough energy to break chemical bonds. It has the potential to damage DNA.
Photochemical ozone formation	Photochemical ozone formation is caused by emissions that react with the light energy of the sun.
Acidification	Acidification is caused by direct outlets of acids or by outlets of gases that form acid in contact with air humidity and are deposited to soil and water. These acid depositions have negative impacts on natural ecosystems and the man-made environment including buildings.
Terrestrial eutrophication	Terrestrial eutrophication is generally associated with the environmental impacts of excessively high levels of nutrients on land that lead to shifts in species composition and increased biological productivity.
Freshwater eutrophication	Freshwater eutrophication is generally associated with the environmental impacts of excessively high levels of nutrients in fresh water that lead to shifts in species composition and increased biological productivity, for example as algal blooms.

Marine eutrophication	Marine eutrophication is generally associated with the environmental impacts of excessively high levels of nutrients in marine water that lead to shifts in species composition and increased biological productivity, for example as algal blooms.
Freshwater ecotoxicity	Freshwater ecotoxicity is the potential environmental toxicity of residues, leachate, or volatile gases that affect plants and animals. Ecotoxic substances alter the composition of the species of ecosystems, destabilizing it thereby and additionally threatening sensitive species in their existence.
Land use	Land use is related to use (occupation) and conversion (transformation) of land area by product-related activities such as agriculture, roads, housing, mining etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation.
Water resource depletion	Water resource depletion is caused by the consumption of water resources, which lowers their availability for nature and future generations.
Mineral, fossil & renewable resource depletion	Resource depletion is caused by the consumption of mineral, fossil and renewable resources, thereby lowering their availability for future generations.
Cumulative energy demand	Cumulative energy demand describes the total amount of energy that is needed for the product.

Appendix C – The relevant impact category selection

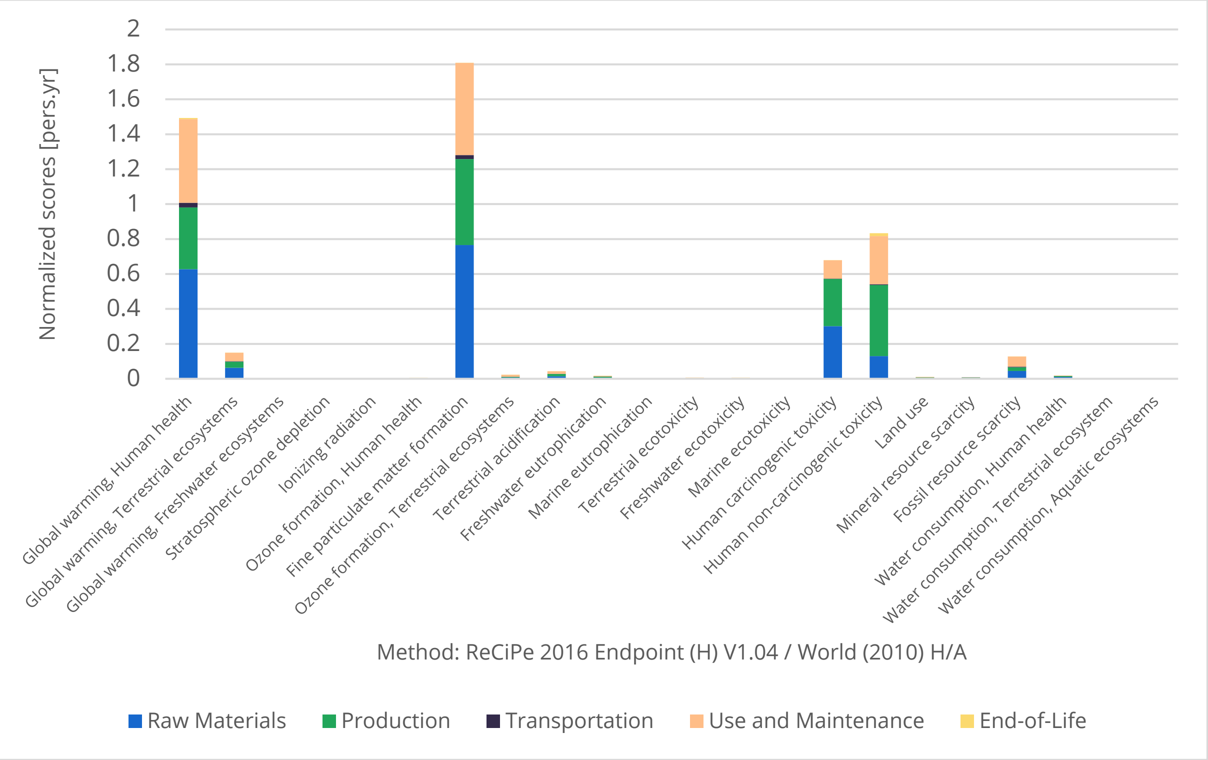

Figure 31 Normalized endpoint scores for 1 Catchy life cycle. Most relevant impact categories: climate change (i.e. global warming), fine particulate matter, human carcinogenic toxicity, human non-carcinogenic toxicity and fossil resource scarcity.

Appendix D – Collected supplier data

Table 6 Overview of the data collected from the supplier inputs

Direction	Material	Amount	Unit	Origin / country of origin	Transport Type	Distance	Unit
Output	**Cage**	**752,00**	**kg**	-	-	-	
Input	Composite	11,67	kg	Flexxcon, Neede, Netherlands	Truck	218	km
Input	EDPM Rubber	15,39	kg	Polson, Papendrecht, Netherlands	Truck	47	km
Input	HMPE	1,63	kg	Vink Kunstoffen, Didam, Netherlands	Truck	162	km
Input	HMPE	90,54	kg	Vink Kunstoffen, Didam, Netherlands	Truck	162	km
Input	Steel S355	125,09	kg	SMS Metaal, Roosendaal	Truck	22	km
Input	Steel S355	426,26	kg	Breedveld Staal, Krimpen, Netherlands	Truck	44	km
Input	Steel S235	17,51	kg	Duiker Mechanical, Zoetermeer, Netherlands	Truck	68	km
Input	Steel AISI 316	63,92	kg	Schaap, Handinxveld-Giessendam, Netherlands	Truck	55	km
Input	Coating -baffles	125,09	kg	Rotocoat, Spankeren, Netherlands	Truck	320	km
Input	Coating- frame of the cage	426,26	kg	Staal Straak Weelde Int, Weelde, Netherlands	Truck	146	km
Processing	Coating	13,96	m2	Staal Straak Weelde Int, Weelde, Netherlands	-	-	
	Welding	241	hr	Allseas, Heijningen, Netherlands	-	-	
Output	**Floating Boom**	**1153,54**	**kg**	-	-	-	
Input	Dyneema (UHMWPE)	77	kg	Geopex, Gouderak, Netherlands	Truck	58	km

Input	EPS60	267,3	kg	Geopex, Gouderak, Netherlands	Truck	58	km
Input	Mix	30	kg	Geopex, Gouderak, Netherlands	Truck	58	km
Input	PP (polypropylene)	49,72	kg	Geopex, Gouderak, Netherlands	Truck	58	km
Input	PVC	179,52	kg	Geopex, Gouderak, Netherlands	Truck	58	km
Input	Steel	550	kg	Geopex, Gouderak, Netherlands	Truck	58	km
Output	**Frame**	**2216,47**	**kg**	**-**	**-**	**-**	
Input	Composite polyester + glass	85,92	kg	Flexxcon, Neede, Netherlands	Truck	218	km
Input	EPS 60	74,52	kg	Geopex, Gouderak, Netherlands	Truck	58	km
Input	HMPE	46,18	kg	Vink Kunstoffen, Didam, Netherlands	Truck	162	km
Input	HMPE	25,96	kg	Vink Kunstoffen, Didam, Netherlands	Truck	162	km
Input	PVC	46,01	kg	Geopex, Gouderak, Netherlands	Truck	58	km
Input	reHDPE	22,88	kg	BV Europe 90, Sint-Oedenrode, Netherlands	Truck	115	km
Input	Steel S355	1809,50	kg	Breedveld Staal, Krimpen, Netherlands	Truck	44	km
Input	Steel AISI 316	95,81	kg	Duiker Mechanical, Zoetermeer, Netherlands	Truck	68	km
Input	Steel AISI 316	9,69	kg	Schaap, Handinxveld-Giessendam, Netherlands	Truck	55	km
Output	**Mooring boom (long)**	**571,06**	**kg**	**-**	**-**	**-**	
Input	Dyneema (UHMWPE)	109,09	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Dyneema (UHMWPE)	10,00	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km

Input	Dyneema (UHMWPE)	12,17	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Steel	70,20	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Steel	65,40	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Steel	234,00	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Steel	70,20	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Output	**Mooring boom (small)**	**4,24**	**kg**	**-**	**-**	**-**	
Input	Dyneema (UHMWPE)	0,16	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Dyneema (UHMWPE)	0,54	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Steel	3,54	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Output	**Rigging**	**38,10**	**kg**	**-**	**-**	**-**	
Input	Dyneema (UHMWPE)	5,40	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Steel	12,70	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Input	Steel	20,00	kg	Lankhorst Touwfabrieken, Dordrecht,	Truck	38	km
Output	**Spud Piles**	**10974,12**	**kg**	**-**	**-**	**-**	
Input	Coating (scrap)	27,6	kg	Simon BV, Rotterdam, Netherlands	Truck	38	km
Input	Steel (scrap)	10946,52	kg	Allseas, Heijningen, Netherlands	Truck	38	km
Processing	Coating of the piles	45,9	m2	Simon BV, Rotterdam, Netherlands	-	-	-

Appendix E – Collected maintenance data

Table 7 Overview of the data collected the maintenance inputs

Direction	Material	Amount	Unit	Frequency
	Cage			
Processing	Lifting by crane	3	hr	every 2 months
	Transport cages	1504	kg	every 2 months
Processing	Coating	11,3	kg	every 5 years
	Transport of Catchy	3720,46	kg	every 5 years
	Frame			
Input	PVC	46,01	kg	every 5 years
	Floating boom			
Input	Dyneema (UHMWPE)	77	kg	every 3 years
Input	PP (polypropylene)	49,72	kg	every 3 years
Input	PVC	179,52	kg	every 3 years
Processing	Fuel boat for demobilisation and re-installation	58,5	kg	every 3 years
	Mooring boom (long)			
Input	Dyneema (UHMWPE)	109,085	kg	every 3 years
Input	Dyneema (UHMWPE)	10	kg	every 3 years

Input	Dyneema (UHMWPE)	12,17	kg	every 3 years
Input	Steel	70,2	kg	every 3 years
Input	Steel	65,4	kg	every 3 years
Input	Steel	234	kg	every 3 years
Input	Steel	70,2	kg	every 3 years
	Mooring boom (small)			
Input	Dyneema (UHMWPE)	0,1605	kg	every 3 years
Input	Dyneema (UHMWPE)	0,535	kg	every 3 years
Input	Steel	3,54	kg	every 3 years
	Rigging			
Input	Dyneema (UHMWPE)	5,4	kg	every 2 years
Input	Steel	12,7	kg	every 2 years
Input	Steel	20	kg	every 2 years

Appendix F – Impact assessment results

Table 8 LCIA results for one Catchy (cradle-to-grave) per life cycle phase.

Impact category	Unit	Total	Raw Materials	Production	Transportation	Use	End-of-Life
Global warming	kg CO2 eq	3,78E+04	1,61E+04	8,84E+03	6,87E+02	1,21E+04	1,58E+02
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	2,89E+01	1,33E+01	8,60E-01	1,53E+01	1,11E-02
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	5,63E+02	1,02E+03	1,62E+01	3,51E+02	6,20E+01
Marine ecotoxicity	kg 1,4-DCB	2,68E+03	7,68E+02	1,33E+03	2,77E+01	4,66E+02	8,45E+01
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	2,15E+03	1,86E+03	1,45E+01	6,87E+02	3,52E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	4,01E+04	1,35E+04	1,77E+04	5,05E+02	6,64E+03	1,78E+03
Fossil resource scarcity	kg oil eq	1,11E+04	4,73E+03	2,29E+03	2,38E+02	3,86E+03	1,44E+00
CED	MJ	5,95E+05	2,40E+05	1,52E+05	1,13E+04	1,92E+05	7,02E+01

Table 9 LCIA results for one Catchy (cradle-to-grave) per supplier.

Impact category	Unit	Nonmaterial	Allseas	Flexxcon	Polson	Vink	SMS Metaal	Breedveld	Duiker	Schaap	Geopex	BV Europe	Lankhorst
Global warming	kg CO2 eq	3,70E+02	4,90E+02	8,69E+01	3,85E+02	1,60E+03	9,68E+03	7,71E+02	9,59E+02	6,67E+03	3,39E+01	6,37E+03	3,70E+02
Fine particulate matter formation	kg PM2.5 eq	9,09E-01	7,48E-01	1,55E-01	3,96E-01	2,07E+00	1,65E+01	2,38E+00	3,14E+00	9,01E+00	3,49E-02	1,05E+01	9,09E-01
Freshwater ecotoxicity	kg 1,4-DCB	4,27E+01	1,93E+01	5,37E+00	3,37E+01	1,15E+02	6,92E+02	6,19E+01	7,74E+01	3,31E+02	2,99E+00	4,70E+02	4,27E+01
Marine ecotoxicity	kg 1,4-DCB	5,86E+01	2,56E+01	7,11E+00	4,50E+01	1,55E+02	9,06E+02	8,62E+01	1,09E+02	4,34E+02	4,00E+00	6,16E+02	5,86E+01
Human carcinogenic toxicity	kg 1,4-DCB	1,40E+02	1,71E+01	3,43E+00	2,08E+01	2,20E+02	1,83E+03	2,35E+02	3,04E+02	5,34E+02	1,85E+00	1,18E+03	1,40E+02
Human non-carcinogenic toxicity	kg 1,4-DCB	6,72E+02	5,71E+02	1,19E+02	6,12E+02	3,29E+03	1,28E+04	1,16E+03	1,46E+03	6,20E+03	5,43E+01	8,67E+03	6,72E+02
Fossil resource scarcity	kg oil eq	1,05E+02	1,62E+02	5,35E+01	8,05E+01	3,73E+02	2,36E+03	1,84E+02	2,32E+02	2,61E+03	7,05E+00	1,53E+03	1,05E+02
CED	MJ	1,59E+05	6,19E+03	8,71E+03	2,68E+03	7,62E+03	2,07E+04	1,35E+05	1,14E+04	1,45E+04	1,39E+05	6,74E+02	1,59E+05

Table 10 LCIA results for one Catchy (cradle-to-grave) per material of the parts.

Impact category	Unit	Composite	Rubber	Steel	(U)HMPE	EPS60	PET	PP	PVC	Non-material
Global warming	kg CO2 eq	4,82E+02	8,69E+01	2,02E+04	1,21E+03	1,62E+03	1,16E+02	3,81E+02	2,30E+03	1,15E+04
Fine particulate matter formation	kg PM2.5 eq	7,37E-01	1,55E-01	3,63E+01	1,39E+00	1,48E+00	1,51E-01	3,45E-01	3,38E+00	1,45E+01
Freshwater ecotoxicity	kg 1,4-DCB	1,90E+01	5,37E+00	1,42E+03	1,09E+02	1,64E+01	5,41E+00	1,19E+01	1,32E+02	2,98E+02
Marine ecotoxicity	kg 1,4-DCB	2,52E+01	7,11E+00	1,88E+03	1,45E+02	2,24E+01	7,09E+00	1,54E+01	1,71E+02	4,08E+02
Human carcinogenic toxicity	kg 1,4-DCB	1,67E+01	3,43E+00	3,95E+03	7,04E+01	3,89E+01	4,03E+00	9,68E+00	8,53E+01	5,41E+02
Human non-carcinogenic toxicity	kg 1,4-DCB	5,63E+02	1,19E+02	2,76E+04	2,05E+03	4,49E+02	1,00E+02	2,12E+02	2,34E+03	6,63E+03
Fossil resource scarcity	kg oil eq	1,60E+02	5,35E+01	4,86E+03	2,83E+02	7,43E+02	5,36E+01	2,82E+02	9,83E+02	3,70E+03
CED	MJ	8,51E+03	2,68E+03	2,78E+05	2,22E+04	3,80E+04	2,81E+03	1,42E+04	5,11E+04	1,77E+05

Table 11 LCIA results for one Catchy (cradle-to-grave) of the comparison for different lifetimes.

Impact category	Unit	5 years	10 years (default)	20 years
Global warming	kg CO2 eq	2,79E+04	3,78E+04	5,76E+04
Fine particulate matter formation	kg PM2.5 eq	4,47E+01	5,84E+01	8,58E+01
Freshwater ecotoxicity	kg 1,4-DCB	1,63E+03	2,01E+03	2,78E+03
Marine ecotoxicity	kg 1,4-DCB	2,17E+03	2,68E+03	3,70E+03
Human carcinogenic toxicity	kg 1,4-DCB	3,96E+03	4,72E+03	6,25E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	3,23E+04	4,01E+04	5,56E+04
Fossil resource scarcity	kg oil eq	7,93E+03	1,11E+04	1,75E+04
CED	MJ	4,33E+05	5,95E+05	9,19E+05

Table 12 LCIA results for one Catchy (cradle-to-grave) for the sensitivity analyses: burden free piles vs. burdened piles, unalloyed vs low alloyed steel and 1kg processing vs. 0.5 processing.

Impact category	**Unit**	**Burden free piles (def.)**	**Burdened piles**	**Unalloyed (def.)**	**Low-alloyed**	**1 kg processing (def.)**	**.5 kg processing**
Global warming	kg CO2 eq	3,78E+04	6,22E+04	3,78E+04	3,66E+04	3,78E+04	3,33E+04
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	1,02E+02	5,84E+01	6,16E+01	5,84E+01	5,17E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	2,68E+03	2,01E+03	3,86E+03	2,01E+03	1,44E+03
Marine ecotoxicity	kg 1,4-DCB	2,68E+03	3,60E+03	2,68E+03	5,02E+03	2,68E+03	1,94E+03
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	1,12E+04	4,72E+03	9,90E+03	4,72E+03	3,68E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,01E+04	5,99E+04	4,01E+04	5,88E+04	4,01E+04	3,11E+04
Fossil resource scarcity	kg oil eq	1,11E+04	1,64E+04	1,11E+04	1,10E+04	1,11E+04	9,96E+03
CED	MJ	5,95E+05	8,63E+05	5,95E+05	5,99E+05	5,95E+05	5,19E+05

Table 13 LCIA results for one Catchy (cradle-to-grave) for the sensitivity analysis *avoided plastic*, comparison of years and yield.

Impact category	**Unit**	**1 year - 10kg**	**10 years - 10kg**	**20 years - 10kg**	**1 year - 64kg**	**10 years - 64kg**	**20 years - 64kg**
Global warming	kg CO2 eq	1,97E+04	3,45E+04	5,10E+04	1,79E+04	1,66E+04	1,52E+04
Fine particulate matter formation	kg PM2.5 eq	3,33E+01	5,42E+01	7,74E+01	3,10E+01	3,15E+01	3,20E+01
Freshwater ecotoxicity	kg 1,4-DCB	1,34E+03	2,13E+03	3,02E+03	1,40E+03	2,77E+03	4,29E+03
Marine ecotoxicity	kg 1,4-DCB	1,78E+03	2,83E+03	4,01E+03	1,86E+03	3,67E+03	5,69E+03
Human carcinogenic toxicity	kg 1,4-DCB	3,35E+03	4,79E+03	6,38E+03	3,39E+03	5,12E+03	7,05E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	2,64E+04	4,31E+04	6,16E+04	2,80E+04	5,92E+04	9,38E+04
Fossil resource scarcity	kg oil eq	5,18E+03	9,18E+03	1,36E+04	4,13E+03	-1,33E+03	-7,39E+03
CED	MJ	2,94E+05	5,02E+05	7,32E+05	2,44E+05	-3,82E+03	-2,79E+05

Table 14 LCIA results for one Catchy (cradle-to-grave) for the sensitivity analysis *end-of-life* scenario.

Impact category	Unit	Expected (default)	Worst case	Do nothing
Global warming	kg CO2 eq	3,78E+04	3,96E+04	3,77E+04
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	5,88E+01	5,84E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	2,14E+03	1,95E+03
Marine ecotoxicity	kg 1,4-DCB	2,68E+03	2,85E+03	2,59E+03
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	4,75E+03	4,72E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,01E+04	4,24E+04	3,83E+04
Fossil resource scarcity	kg oil eq	1,11E+04	1,12E+04	1,11E+04
CED	MJ	5,95E+05	5,97E+05	5,95E+05

Uncertainty analysis

Table 15 Mean, standard deviation, 2.5% lower limit and 97.5% upper limit for one Catchy (cradle-to-grave), determined with 10.000 iterations Monte Carlo analysis.

Impact category	Unit	Mean	Standard dev.	2.5% limit	97.5% limit
Global warming	kg CO2 eq	3,78E+04	2,70E+03	3,31E+04	4,37E+04
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	6,08E+00	4,86E+01	7,21E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	6,62E+02	1,47E+03	2,87E+03
Marine ecotoxicity	kg 1,4-DCB	1,27E+01	5,65E+00	5,69E+00	2,69E+01
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	1,97E+03	2,53E+03	9,12E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,04E+04	3,00E+04	2,64E+04	6,79E+04
Fossil resource scarcity	kg oil eq	1,11E+04	8,01E+02	9,71E+03	1,28E+04
CED	MJ	5,95E+05	4,27E+04	5,18E+05	6,85E+05

Mitigation measures

Table 16 LCIA results for one Catchy (cradle-to-grave) for the mitigation measure *fit for purpose*.

Impact category	**Unit**	**No reduction (default)**	**Little reduction (10%)**	**Signif. reduction (20%)**
Global warming	kg CO2 eq	3,78E+04	3,57E+04	3,37E+04
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	5,47E+01	5,10E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	1,86E+03	1,71E+03
Marine ecotoxicity	kg 1,4-DCB	2,68E+03	2,48E+03	2,28E+03
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	4,31E+03	3,90E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,01E+04	3,72E+04	3,43E+04
Fossil resource scarcity	kg oil eq	1,11E+04	1,06E+04	1,01E+04
CED	MJ	5,95E+05	5,66E+05	5,37E+05

Table 17 LCIA results for one Catchy (cradle-to-grave) for the mitigation measure *recycled steel.*

Impact category	**Unit**	**No recycled steel (default)**	**50-50 recycled steel**	**Recycled steel**
Global warming	kg CO2 eq	3,78E+04	3,41E+04	3,04E+04
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	5,04E+01	4,24E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	1,99E+03	1,97E+03
Marine ecotoxicity	kg 1,4-DCB	2,68E+03	2,64E+03	2,60E+03
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	3,97E+03	3,22E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,01E+04	3,82E+04	3,63E+04
Fossil resource scarcity	kg oil eq	1,11E+04	1,03E+04	9,55E+03
CED	MJ	5,95E+05	5,58E+05	5,21E+05

Table 18 LCIA results for one Catchy (cradle-to-grave) for the mitigation measure *emptying optimization.*

Impact category	**Unit**	**Emptying monthly (default)**	**Emptying optimized - 2 times a year**
Global warming	kg CO2 eq	3,78E+04	2,94E+04
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	4,83E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	1,96E+03
Marine ecotoxicity	kg 1,4-DCB	2,68E+03	2,59E+03
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	4,55E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,01E+04	3,88E+04
Fossil resource scarcity	kg oil eq	1,11E+04	8,46E+03
CED	MJ	5,95E+05	4,72E+05

Table 19 LCIA results for one Catchy (cradle-to-grave) for the mitigation measure *all measures combined.*

Impact category	**Unit**	**No mitigation measures (default)**	**All measures combined**
Global warming	kg CO2 eq	3,78E+04	2,44E+04
Fine particulate matter formation	kg PM2.5 eq	5,84E+01	3,03E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,01E+03	1,49E+03
Marine ecotoxicity	kg 1,4-DCB	2,68E+03	1,96E+03
Human carcinogenic toxicity	kg 1,4-DCB	4,72E+03	2,47E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,01E+04	2,75E+04
Fossil resource scarcity	kg oil eq	1,11E+04	7,83E+03
CED	MJ	5,95E+05	4,38E+05

Table 20 LCIA results for one Catchy (cradle-to-grave) for the mitigation measure *biomass composting instead of incineration.*

Impact category	**Unit**	**Biomass incineration**	**Biomass composting**
Global warming	kg CO2 eq	3,45E+04	3,46E+04
Fine particulate matter formation	kg PM2.5 eq	5,42E+01	5,48E+01
Freshwater ecotoxicity	kg 1,4-DCB	2,13E+03	2,10E+03
Marine ecotoxicity	kg 1,4-DCB	2,83E+03	2,80E+03
Human carcinogenic toxicity	kg 1,4-DCB	4,79E+03	4,75E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	4,31E+04	4,17E+04
Fossil resource scarcity	kg oil eq	9,18E+03	9,18E+03
CED	MJ	5,02E+05	5,02E+05

Appendix G – Sensitivity coefficient

The sensitivity coefficient can be calculated by evaluating two scenarios. In the two scenarios one input parameter is changed. The consequent change in the environmental impacts is evaluated as well. This is done per impact category. The relative change in the input parameter and in the output environmental impacts are compared to determine the sensitivity coefficient, see equation 1.

$$S_{\mathrm{In}} = \left(\frac{\Delta \mathrm{output}}{\mathrm{output}}\right) / \left(\frac{\Delta \mathrm{input}}{\mathrm{input}}\right) \qquad (1)$$

A coefficient of 0.25 indicated that the environmental impact will increase with 25% if the input parameter is increased by 100%. Parameters are considered sensitive when the average of coefficient across all impact categories is 0.3 or larger, and if the highest coefficient is 0.5 or larger. Four assumptions and modeling choices were studied: The lifetime of Catchy, the use of non-scrap piles, the modelling of the steel and the end-of-life scenario. The sensitivity of the end-of-life scenarios were found to be insignificant (relative change <7%) and are excluded from the main report. The graphs can be found in the appendix.

Appendix H – Sensitivity analysis of end-of-life scenarios

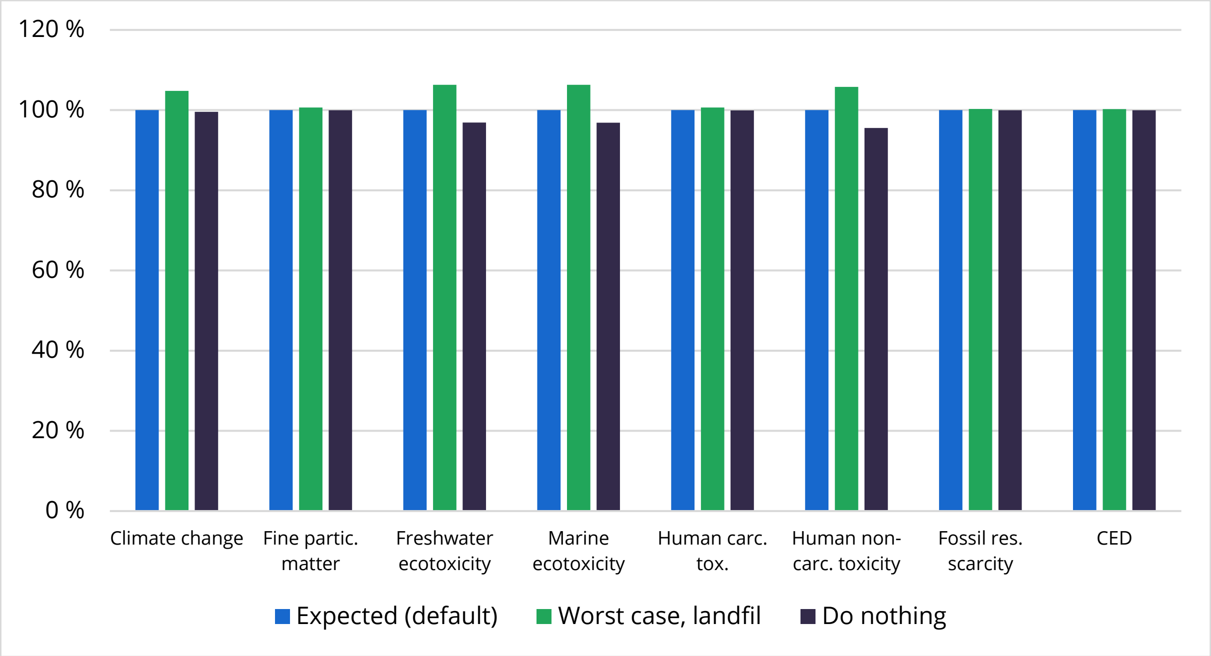

Figure 32 Comparison of the relative characterized results for the relevant impact categories for 1 Catchy with respective the expected waste treatment scenario for Catchy, the worst-case scenario and the "do-nothing" scenario.

Appendix I – Pedigree matrix

In practice, all data used in an LCA study is a mixture of measured, estimated, and calculated data. The quality of data is rarely homogenous. In this study, some data is very reliable while some has been estimated. To evaluate the quality of data used for modeling, Data Quality Indicators (DQI) have been assigned to the most relevant flows in the model, using the data quality matrix approach. These scores have also been used to assess uncertainties on the data and subsequently assess the uncertainty of the model and the results.

The method to change the point estimates to probability distributions is based on the pedigree matrix developed by Weidema and Wesnaes[79]. Each flow type is attributed to a basic uncertainty factor[80], which is then combined with "additional uncertainty factors" using the following equation to calculate a squared geometric standard deviation:

$$SSD_{g95} = \sqrt{\exp\,[\ln(U_1)^2 + \ln(U_2)^2 + \ln(U_3)^2 + \ln(U_4)^2 + \ln(U_5)^2 + \ln(U_6)^2 + \ln(U_b)^2}$$

With:

U_1	uncertainty factor of reliability
U_2	uncertainty factor of completeness
U_3	uncertainty factor of temporal correlation
U_4	uncertainty factor of geographic correlation
U_5	uncertainty of other technological correlation
U_6	uncertainty of sample size (obsolete indicator)

The six types of DQI are evaluated by the Pedigree matrix[79] by using scores from 1 to 5. Scores have been assigned to the data in the SimaPro model based on the criteria presented in the Pedigree matrix as shown in Table 21.

Table 21 Pedigree matrix

DQI	Description	Value
Reliability	Unspecified	N/A
	Verified data based on measurements	1
	Verified data based on assumptions or non-verified data based on measurements	2
	Non-verified data partly based on qualified estimates	3
	Qualified estimate (e.g., by industrial expert)	4
	Non-qualified estimate	5
Completeness	Unspecified	N/A
	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	1
	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	2
	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods	3
	Representative data from only one site relevant for the market considered or some sites but from shorter periods	4
	Representative unknown or data from a small number of sites and from shorter periods	5
Temporal correlation	Unspecified	N/A
	Less than 3 years of difference to the time period of the dataset	1
	Less than 6 years of difference to the time period of the dataset	2
	Less than 10 years of difference to the time period of the dataset	3
	Less than 15 years of difference to the time period of the dataset	4

	Age of data unknown or more than 15 years of difference to the time period of the dataset	5
Geographical correlation	Unspecified	N/A
	Data from area under study	1
	Average data from larger area under study is included	2
	Data from area with similar production conditions	3
	Data from area with slightly similar production conditions	4
	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)	5
Further technological correlation	Unspecified	N/A
	Data from enterprises, processes and materials under study	1
	Data from processes and materials under study (i.e., Identical technology) but from different enterprises	2
	Data from processes and materials under study but from different technology	3
	Data on related processes or materials	4
	Data on related processes on laboratory scale or from different technology	5
Sample size	Obsolete indicator - Unspecified used	N/A