Chapter 7
Life Cycle Assessment of Fishing and Aquaculture Rope Recycling

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Abstract In this chapter, we assess the environmental footprint of the production of recycled plastic granulate made of waste ropes from the fishing/aquaculture industries. The end-of-life treatment of waste fishing and aquaculture gear is an important factor in solving the marine plastic crisis. The improvement of waste management on land is thought to be one of the key strategies for tackling marine plastic challenges. Moreover, in terms of the circular economy, recycling is viewed as a more desirable end-of-life treatment than incineration and landfilling. Meanwhile, it is important to understand the environmental impacts of recycling processes to avoid problem shifting. The publication of environmental impact data on the recycling of fishing/aquaculture gear can assist policy makers and waste managers, amongst other stakeholders, in making decisions about end-of-life treatments. Life cycle assessment (LCA) is a standardised methodology for the assessment of the environmental impacts of a product across its full life cycle, from raw material acquisition through to end-of-life phases. In this chapter, we perform an LCA of fishing and aquaculture rope recycling. We begin with the acquisition of waste polypropylene/polyethylene (PP/PE) ropes from the fishing and aquaculture industries, move to the production of recycled granulate and end with delivery to the customer. We assess the environmental footprint of 1000 kg of PP/PE granulate across a range of impact categories, including global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The core processes account for 40% of the total GWP emissions with the upstream and downstream processes accounting for 30% of the emissions each. A critical contributor to GWP emissions from PP/PE rope recycling comes from diesel production and consumption across the product life cycle. Finally, the global warming potential, acidification potential, and eutrophication potential of recycled PP/PE are significantly lower when compared to virgin PP and PE.

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7.1 Introduction

The global demand for protein and nutrition is driving the expansion of fishing and aquaculture industries across the globe (Hicks et al. 2019). The predicted doubling of the demand for fish by 2050 (Naylor et al. 2021) raises concerns about the sustainability of the expansion of the aquaculture and fisheries industries (Costello et al. 2020). The aquaculture and fisheries industries are heavily reliant on plastic equipment to house, feed, and capture fish. The volume of fishing and aquaculture gear lost to the environment is of particular interest due to the damaging effects they can have on individual species and ecological systems (Macfadyen et al. 2009). Economic losses are also evident through the loss of potential fisheries and the entangling of gear with propellers as well as other mechanisms. Large economic investments in fishing and aquaculture gear mean that losses to the natural environment often occur by accident. However, it is believed that gear is also purposefully lost to the environment to avoid costly port reception facility waste fees (Sherrington et al. 2016). A recent study by Deshpande et al. (2020) estimated that 380 tonnes of fishing gear from Norwegian fishers enter the sea each year. Fishing and aquaculture gear recyclers around Europe have begun to take up the challenge and have started to produce recycled plastic granulate for use in a range of products. However, it remains important to ensure that the environmental impact of waste plastic recycling is calculated to provide a benchmark for comparison with both virgin plastic production and other types of end of life treatments. Life cycle assessment (LCA) is an internationally recognised and standardised methodology for the environmental impact assessment of products and product systems (European Commission 2010). In this chapter, we will be estimating the environmental impacts of recycling fishing and aquaculture plastic rope using data from a case company in Norway.

7.2 Methodology

The environmental impacts related to the recycling of fishing and aquaculture rope are analysed using the standardised life cycle assessment method (LCA) (ISO 2006). The LCA methodology consists of four phases, as per ISO 14040 (ISO 2006). The first phase is setting the goal and scope of the study. This consists of defining the system boundaries and the declared unit. The second phase is the life cycle inventory (LCI), whereby all of the inputs and outputs of raw materials and energy to each individual process within the production life cycle are accounted for. The third phase is the life cycle impact assessment (LCIA), which involves calculating the environmental impact of each input and output flow throughout the production life cycle. The final phase is interpretation, which consists of analysing the data from the LCA using various visualisations. A detailed description of the LCA methodology is freely available from the European Commission (2010). In this study, the Gabi ts software was used to carry out the LCA with raw annual data collected in 2020 (for the production year 2019). Raw data was collected directly from the case recycling company using a mixture of meetings and data collection sheets. The processes used in the LCA and the final impact assessment were also validated by the case company before being included in this chapter.

7.2.1 Goal and Scope

The objective of this LCA is to estimate the environmental impacts related to the recycling of waste PP/PE fishing and aquaculture ropes into PP/PE granulate. PP/PE (polypropylene/polyethylene).

Case Company

Our case company is a plastics recycler based in Norway. The company is engaged in recycling plastic from both the fishing and aquaculture industries. They recycle PP/PE ropes from the fishing and aquaculture industries industry. Our goal is therefore to estimate the environmental impacts of recycling PP/PE from the fishing and aquaculture industry.

Declared Unit

The declared unit is the production of 1000 kg of recycled polypropylene/polyethylene (PP/PE) granulate from waste fishing/aquaculture rope. PP/PE granulate is used to replace virgin plastics in the manufacture of plastic products across a wide range of industries, from the furniture to the construction industry.

System Boundaries

The system boundaries are set at the point of collection of the waste plastic fishing/aquaculture rope (upstream processes) and include all processes relating to the processing of the fishing/aquaculture rope into new plastic granulate (core processes) and the delivery to the customer (downstream processes), as shown in Fig. 7.1. The system boundaries do not extend to the initial production of the PP/PE rope or to the use of the plastic granulate by downstream customers. The boundaries are set in order to compare recycled plastics to virgin plastics. Processes included in the study are listed and explained, as well as the way in which data was collected, in Table 7.1.

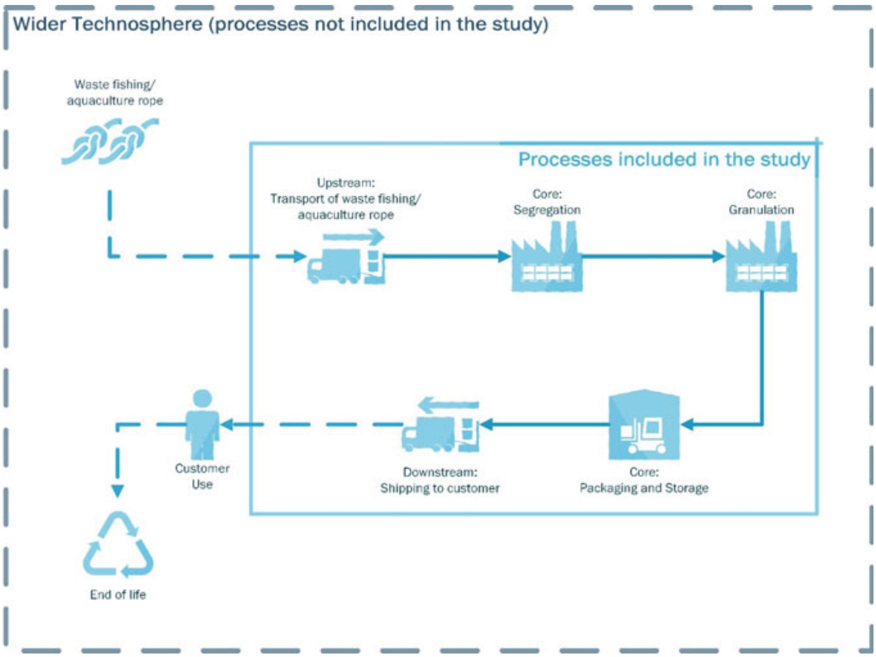

Fig. 7.1 System diagram of recycled PP/PE granulate production from waste fishing/aquaculture rope

7.2.2 Life Cycle Inventory

Foreground data on the upstream, core, and downstream processes for the year 2019 was obtained directly from as the case company in 2020 using data collection sheets and meetings/interviews. Background data was chosen from the Gabi Sphera database.

7.2.2.1 Life Cycle Impact Assessment

The environmental impact of the production of plastic granulate from waste fishing/aquaculture rope was obtained using categories from the CML 2001 characterisation model, as shown in Table 7.2. CML 2001 was chosen as it is a well-established, widely used, and scientifically supported method operationalizing the ISO 14040 standard series (European Commission 2010). CML 2001 uses characterisation factors developed from peer reviewed scientific literature, such as those found in the reports from Intergovernmental Panel for Climate Change (IPCC).

Table 7.1 Processes included in the Life Cycle Assessment of recycled PP/PE granulate production from waste fishing/aquaculture rope

Upstream	Transport	Truck with trailer used to collect waste fishing/aquaculture rope. Case company communicated that all of their trucks are Euro 6 or better and specified the tonnage, therefore the Gabi Truck Process GLO: Truck-trailer, Euro 6, 34–40 t grow weight/27 t payload was used (see Table 7.4)
Core	Segregation	Specific data collected on the mass of waste rope, that could not be recycled due to chemical coatings, and the waste management used for end of life. A generic data set from Gabi was utilised to model this process, EU-28: Plastic waste on landfill ts. The Gabi Truck Process GLO: Truck-trailer, Euro 6, 34–40 t grow weight/ 27 t payload was used for transport to the landfill site
	Forklift	Specific data was collected from the case company for the diesel used to move waste fishing/aquaculture rope around the factory. A proxy data set for the forklift process was used for diesel consumption, truck Euro 6, up to 7.5 t gross weight
	Granulation	Specific data was collected from case company on the electricity required to shred and granulate fishing/aquaculture rope waste. The generic Gabi data set was utilized to model this process, NO: Electricity grid mix ts
	Water for cleaning shredded material	The volume of water used to clean material is specific data collected from case company. The Gabi process used to model this was the EU-28: Process water ts
	Wastewater treatment	The volume of water going to the wastewater treatment plant was assumed to be the same as the water input to the system. The Gabi process used to model this was the EU-28: Municipal wastewater treatment (mix) ts
	Waste production	Specific data was collected on the mass of waste produced by case company during the granulation phase and the type of waste management used for end of life, which was incineration. A generic data set from Gabi was utilised to model this process, EU-28: Waste incineration of plastics ts
	Storage	Plastic granulate should be stored at a temperature of 21 °C in order to keep it dry. The excess heat from the granulation machine is used to maintain the temperature at case company, reducing the need for additional heating sources and thus additional processes in this system
	Forklift	Specific data was collected from the case company for the diesel used to store the new granulate at the case company's facility. A proxy data set for the forklift process was used for diesel consumption, truck Euro 6, up to 7.5 t gross weight (see Table 7.4)
	Packaging	Specific data was collected from case company on the type, mass and number of storage bags used to store each 1000 kgs of granulate. The generic data set from Gabi, EU-28: Polypropylene fibers (PP) ts was used to model this process. Transport from the bag production facility to the case company was assumed to be a GLO: Truck-trailer, Euro 6, 34–40 t gross weight

(continued)

Table 7.1 (continued)

Downstream	Delivery to customer	Truck with trailer used to deliver the recycled PP/PE granulate to the customer. The case company communicated that all of their trucks are Euro 6 or better and specified the tonnage, therefore the Gabi Truck Process GLO: Truck-trailer, Euro 6, 34–40 t grow weight/27 t payload was used (see Table 7.4)

Table 7.2 Impact categories modelled in the Life Cycle Assessment of recycled PP/PE granulate production from waste fishing/aquaculture rope

Impact category	Unit (expressed per declared unit)
Global warming potential, GWP	Kg CO_2-equiv
Acidification potential of soil and water, AP	Kg SO_2-equiv
Eutrophication potential, EP	Kg PO_4-equiv
Abiotic depletion potential—elements	Kg Sb-equiv
Abiotic depletion potential—fossil fuels	MJ, net calorific value
Net use of freshwater	m^3 eq
Hazardous waste	Kg
Non-hazardous waste	Kg
Total use of non-renewable primary energy resources (PENRT)	MJ
Total use of renewable primary energy resources (PERT)	MJ

Global Warming Potential (GWP)

Global warming or climate change is a global problem resulting from the infrared radiative forcing effects of greenhouse gases. Global warming potential in life cycle assessment is measured in kg CO_2-equivalent or carbon dioxide equivalents. Average temperature rises across the globe as a result of greenhouse gas emissions can be viewed as an exogenic pressure as, although emissions may be the result of local activities, the consequences from those emissions are at a global level.

Acidification Potential (AP)

Acidification is also a global problem resulting from the emissions of acid compounds from human activities. Acidification in life cycle assessment is measured using emissions kgs of SO_2-equivalent, or sulphur dioxide equivalents. Acidification of our oceans leads to the reduction in the productivity of low trophic level organisms, such as plankton and shellfish. These reductions have a knock-on negative effect on fish stocks, which feed on these smaller organisms. Acidification can also be thought of as an exogenic pressure, as it is a global problem which will have impacts locally.

Eutrophication Potential (EP)

The emissions of phosphates and nitrates from activities on the land lead to run off of these nutrients into water bodies causing eutrophication, or the enrichment of water bodies with nutrients. The productivity of plant species, such as algae, in water bodies, is limited by the concentration of key nutrients, such as nitrogen or phosphorus. Eutrophication releases plant species from this limitation and results in algal blooms which can ultimately create dead zones for other species below the hyperproductive algae. Eutrophication is measured in kgs of NO_3-equivalent emissions, or nitrate-equivalent emissions, and can be viewed as an endogenic pressure since these emissions have an effect on the local system.

Abiotic Depletion Potential (ADP Elements)

The depletion of minerals throughout the life cycle of a product is measured using the ADP elements impact category. It is important to understand whether a product system is depleting mineral resources, particularly rarer ones. Rare minerals have a higher weighting in LCA than more common minerals.

Abiotic Depletion Potential (ADP Fossil)

The depletion of fossil (carbon–hydrogen–oxygen) compounds is measured in terms of energy content lost. Production systems which rely heavily on fossil fuels, such as diesel fuel, perform poorly with this impact category.

Hazardous Waste Disposed (HWD) and Non-hazardous Waste Disposed (NHWD)

Hazardous waste can be defined as any waste (solid, liquid, or gas) which has a harmful effect on either humans or the environment.

Net Use of Freshwater (FW)

The volume of freshwater used in industrial processes is of global concern due to issues with water scarcity.

Total use of non-renewable primary energy resources (PENRT) and total use of renewable primary energy resources (PERT)

The energy demand of industrial processes is of interest as it is used as a proxy for the efficiency of a production system.

7.2.2.2 Sensitivity Analysis

Transport is one of the key activities in both upstream and downstream processes within a recycling company's production system. The sensitivity analysis focussed on adjustable parameters related to this process. Sensitivity analysis was performed on all free parameters within the Truck-trailer, Euro 6, 34–40 tonne/27 tonne payload truck data set from Gabi. This data set has 9 free parameters which can be manipulated

Table 7.3 Adjustable, free parameters available in the Gabi sphera Truck Processes, GLO: Truck-trailer, Euro 6, 34–40 tonne/27 tonne payload ts. PPM (parts per million)

Parameter	Data type	Value
Cargo	Case company specific data	1000 kgs
Distance	Case company specific data	7765 km
Payload	Gabi generic default data	27 tonnes
PPM sulphur in diesel fuel	Gabi generic default data	10
% of biogenic C in fuel	Gabi generic default data	5%
% of motorway driving	Gabi generic default data	70%
% of rural driving	Gabi generic default data	23%
% of urban driving	Gabi generic default data	7%
Utilisation	Gabi generic default data	61%

by the user. Since a variety of specific data and generic data was used to model truck transport, it is important to understand where sensitivity within the model exists. The sensitivity of each parameter was assessed by keeping all parameters, apart from the one under assessment, at the default value (Table 7.3). Sensitivity was measured by recording the carbon dioxide equivalent emissions as a result of parameter alternations as the output.

7.3 Results

7.3.1 Life Cycle Inventory

The foreground data was collected from the case company in 2020. The inventory data points are normalised to the production of 1000 kg of recycled PP/PE granulate, as per the declared unit. The data is shown in Table 7.2. Data was collected for the case company's production year 2019. In 2019, the case company collected 642,990 kg of PP/PE ropes from 18 sites (aquaculture, fishers, and waste management companies) ranging from 3.2 to 1421 km distance from their processing site. All PP/PE ropes collected by the case company were segregated into those that can be recycled and those which have to be sent to landfill due to contaminants in rope coating treatments. 10% of all PP/PE ropes collected by the case company in 2019 were sent for landfill. The segregation process also consumes some diesel due to the

Table 7.4 Inventory of foreground data used in the Life Cycle Assessment of recycled PP/PE granulate production from waste fishing/aquaculture rope

	Inventory of foreground data	Per 1000 kg recycled PP/PE
Upstream	PP/PE rope collected	1122 kgs
	Collection transport distance (2019 total)	27,126 km
	Collection sites in Norway (2019 total)	18
	Number of pickups (2019 total)	63
Core	PP/PE rope sent for segregation	1122 kgs
	PP/PE rope sent for landfill	112 kgs
	Distance to landfill	185 km
	PP/PE shredded rope sent for granulation	1010 kgs
	Electricity usage during granulation	345 kw
	Freshwater usage during granulation	100 litres
	Recycled PP/PE granulate produced	1000 kgs
	PP/PE granulate waste sent to incineration	10 kgs
	Distance to incinerator	275 km
	Diesel consumed by forklift	8.83 litres
	Number of PP bags (1600 litres)	1
Downstream	Distance to Norwegian customers (2019 total)	6646 km
	Delivery sites in Norway (2019 total)	7
	Number of drop-offs (2019 total)	10

use of forklifts to move material around the facility. Once segregated, the ropes are fed into the electric granulation machinery which shreds, cleans and granulates the PP/PE. The granulation process requires both electricity and freshwater and results in around 1% loss of waste material which is sent to a local incineration plant. The heat from the granulation machinery is used to heat the storage space housing the recycled PP/PE granulate. Each tonne of material is stored in PP bags which are moved around using a diesel-powered forklift. The case company has customers around Norway and Europe. In this study, the focus was on Norwegian customers who were located at a distance between 527–1842 km from the case company's facility (for the full inventory, see Table 7.4).

7.3.2 Life Cycle Impact Assessment

The environmental impact of the production of 1000 kg of recycled PP/PE granulate from fishing/aquaculture ropes was conducted across a range of impact categories. The results of the impact assessment are found in Fig. 7.2. The core activities account for the majority of environmental impacts with the upstream and downstream, collection and delivery, processes contributing a similar proportion to one

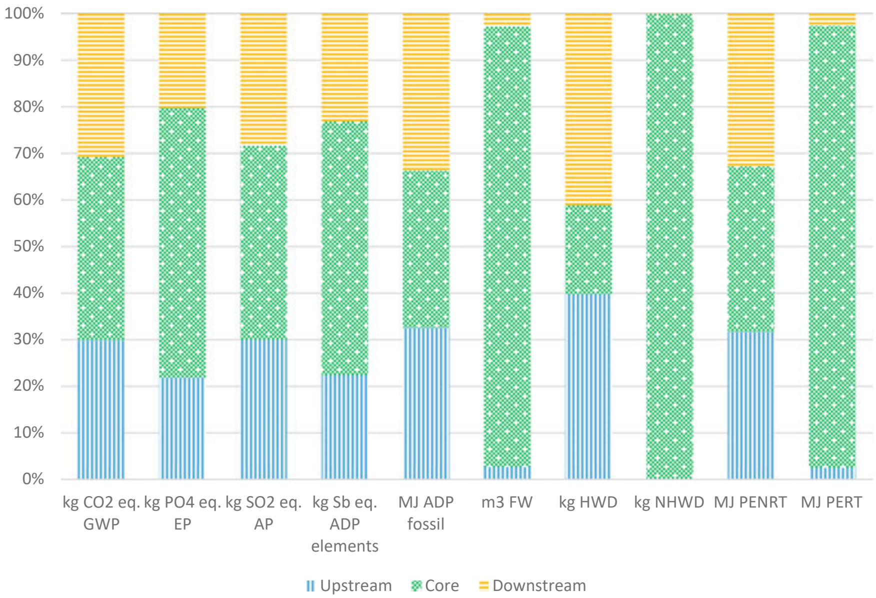

Fig. 7.2 Environmental Impact Assessment of the production of 1000 kgs of recycled PP/PE granulate from waste fishing/aquaculture rope in Norway GWP = Global warming potential, AP = Acidification potential, EP = Eutrophication potential, ADP = Abiotic depletion potential, FW = Net use of freshwater, HWS = Hazardous waste disposed, NHWD = Non-hazardous waste disposed, PENRT = Total use of non-renewable primary energy resources, PERT = Total use of renewable primary energy resources

another. This distribution of impacts across the upstream, core and downstream activities is observed for the majority of impact categories. A different pattern is observed for the the net use of freshwater (FW), non-hazardous waste disposed (NHWD) and the total use of renewable primary energy resources (PERT) whose impacts can be contributed mostly to core activities. A key contributor across the life cycle of the entire product system is diesel production and consumption. Diesel is used for both transport processes, collection and distribution, and core processes, such as the use of a forklift to transport waste ropes and granulate around the recycling facility. The production of 1000 kg of PP/PE granulate requires just 31 kg of diesel and the environmental impacts related to the production and consumption of this diesel makes up 74% of CO_2-equivalent emissions. The contribution of each life cycle phase to multiple environmental impact categories is discussed further below.

Global Warming Potential (GWP)

The carbon equivalent emissions for the production of recycled PP/PE from fishing/aquaculture ropes were estimated to be 184 kg CO_2-equivalents. Core processes account for 40% of GWP emissions (73 kg CO_2-equivalents) with upstream and downstream transport processes both contributing 30% (55 and 57 kg CO_2-equivalent emissions) each. The main contributor across all three phases of the life cycle is diesel production and consumption, with 14 kg and 123 kg CO_2-equivalents emitted by each process respectively. The collection of the ropes using heavy trucks, the use of a forklift to move waste ropes and recycled granulate around the recycling facility and the delivery of the granulate to the customers all require diesel fuel and thus contribute to the majority of the GWP emissions.

Net Use of Freshwater

The use of freshwater for the production of recycled PP/PE from fishing/aquaculture ropes was estimated to be 2.69 m^3 with the majority of water, 2.55 m^3 being used in the core granulation process at the case company's facility. The upstream processes account for 0,07 m^3 freshwater us whilst the downstream processes account for 0.08 m^3.

Eutrophication and Acidification Potential

Eutrophication and acidification potential emissions are greater for the core processes of the case company's production system. Each of the upstream and downstream phases contributed 0.01 kg PO_4 equivalent eutrophication emissions and 0.05 kg SO_2 equivalent acidification emissions whilst the core processes contributed 0.03 and 0.07 respectively. Diesel production and consumption bears the responsibility for these emissions in the upstream and downstream phases whilst the landfilling of 112 kg of waste ropes is responsible for 2.13 kg PO_4 equivalent and 2.15 kg equivalent SO_2 emissions.

Abiotic Depletion Potential

The recycled PP/PE production is attributed to very little consumption of minerals or metals resulting in low impacts in terms of total abiotic depletion of elements of 0.00002 Kg Sb equivalent across all life cycle phases. 2249 MJ of fossil fuels are depleted throughout all life cycle phases of the production system. Diesel consumption across all phases is the main contributor to the depletion of fossil fuels with 81% depleted during this process.

Waste

Waste production can mainly be linked to the core processes. The case company produce around 122 kg of non-hazardous waste during their production processes, which is either landfilled or incinerated. Hazardous waste from the production system stands at 0.0001 kg with diesel production the main contributor.

Total use of non-renewable primary energy resources (PENRT) and total use of renewable primary energy resources (PERT)

The use of non-renewable energy resources (PENRT) is evenly spread across the upstream, core and downstream processes (736, 824 and 761 MJ respectively). In contrast, the total use of renewable resources (PERT) is associated primarily with core processes (1619 MJ), specifically electricity production in Norway, whilst the upstream and downstream processes only use 43 and 44 MJ of renewable energy respectively.

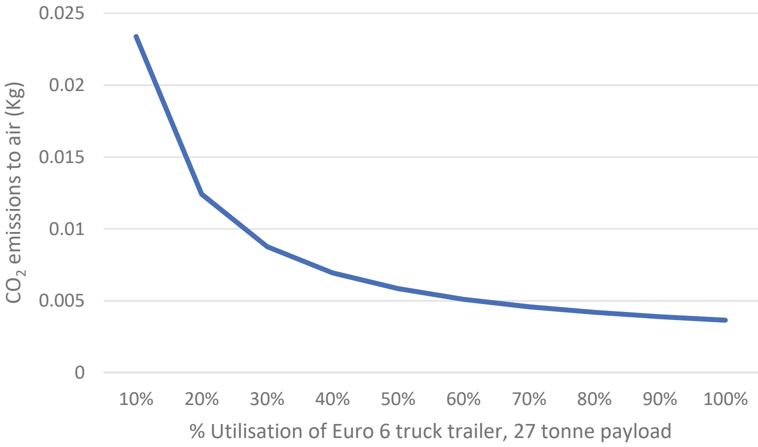

Fig. 7.3 Effects of variation in % utilisation of Euro 6 truck trailer (27 tonne payload) ts data set on CO_2 [Inorganic emissions to air] (kg)

7.3.2.1 Sensitivity Analysis

Sensitivity analysis was performed on greenhouse gas emissions to utilisation, and mass carried/payload is highly sensitive at lower values and less sensitive from around 55% utilisation, as shown in Fig. 7.3. High emissions associated with low utilisation rates are an issue for companies with a focus on transport and should be addressed accordingly. Increasing utilisation rates from 10 to 70% can have an almost fivefold decrease in greenhouse gas emissions from transport.

7.4 Discussion and Conclusion

The main contributor to the environmental impact of the PP/PE recylate production system is the production and consumption of diesel across the life cycle phases. The use of landfill for end-of-life treatment has impacts in terms of eutrophication and acidification, whilst global warming emissions are dominated by the consumption of fossil fuels. The geography of Norway, with its long, winding coastline results in large transport footprints for companies involved in logistics, particularly those interacting with the fishing and aquaculture sector. However, European and International targets to reduce emissions from trucks by 2030 and eliminate emissions by 2050 paint a positive picture of the future for this type of production system, particularly if core processes are also driven by renewable electricity sources.

The PP/PE recyclate production is favourable in terms of environmental impact to the production of virgin PP and PE (Plastics Europe 2014a, b), as seen in Fig. 7.4. The

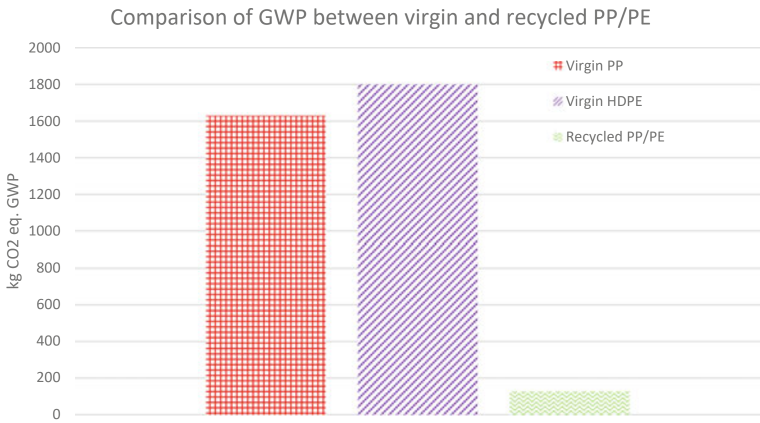

Fig. 7.4 Comparison of kg CO_2 equivalent emissions from the upstream and core production phases of virgin PP, virgin HDPE and recycled PP/PE granulate from fishing/aquaculture gear

production of recycled PP/PE granulate emits between 7 and 8% of the CO_2 equivalent emissions attributed to the production of virgin HDPE and virgin PP for upstream and core processes.

In this chapter, results from a life cycle assessment of recycling PP/PE from waste fishing/aquaculture gear have been presented. Data and models built to perform the assessment are based on technologies and practices in a Norwegian context. When assessing the carbon footprint, results show that PP/PE recycling following the upstream, core, and downstream processes included in our study largely depend on transportation, for in-house processes as well as collection and delivery. The transportation distance, selection of energy carriers, utilisation rates, and speed all contribute to the total greenhouse gas emissions from transport. Some of these conditions could also vary both spatially and temporally. For instance, recyclers located closer to their customer base would, all other things being equal, have a lower fuel consumption and thereby reduced greenhouse gas emissions from transport. Local market conditions, such as supply volumes and frequencies, could also impact utilisation rates. Recyclers operating with larger volumes and higher utilisation rates would also have a lower greenhouse gas emission per declared unit than the results of our study. This may also vary over time. When an extended producer responsibility scheme (EPR) for fishing gear is introduced, European countries will need to establish infrastructure to manage obsolete gear. This could make the collection and distribution of obsolete gear more efficient and predictable, enabling recyclers to reduce the impact of transport logistics.

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