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Fishing gear recycling technologies and practices

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by

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Abstract

The recycling of fishing gear contributes to more sustainable fisheries by supporting responsible fishing gear stewardship. It achieves this by preserving and prolonging the use of valuable gear materials and components, incentivizing the collection and recovery of damaged and end-of-life fishing gears and abandoned, lost or otherwise discarded fishing gears, and by providing a valuable alternative to landfilling. This report reviews current fishing gear recycling technologies and practices, while also summarizing those technical measures and policy and regulatory instruments that can support fishing gear recycling. Finally, it touches on circular economy considerations for fishing gears.

Fishing gear recycling can be undertaken by way of a range of technologies and processes. This report covers primary and secondary (mechanical), tertiary (chemical recycling, chemical recovery and thermal conversion), and quaternary (energy recovery) recycling processes. The chosen recycling method will depend on the type, volume and quality of the fishing gears and associated components available for recycling, including the degree of contamination and degree of polymer purity. It will also depend upon local and regional capacities to support fishing gear recycling, both in technological terms and through effective waste management systems and frameworks.

The range and diversity of fishing gears in use globally and locally ultimately necessitates a combination of recycling measures and complementary interventions that are tailored to the requirements of each country, region, locality and their associated fishing techniques. The inclusion of – as well as the communication between and across – the variety of stakeholders involved with fishing gear recycling is critical. These stakeholders are policymakers, managers and regulators; fishing gear producers, manufacturers, assemblers, vendors and purchasers; fishers; port authorities; waste management agencies; and recycling businesses. Sound collaboration ensures that different stakeholders can support one another's efforts and roles in ensuring that fishing gear is responsibly and efficiently recycled according to the best available and most appropriate technology. This report highlights the need for systemic approaches that align effective fisheries and waste management governance with complementary measures to support fishing gear recycling from the design and manufacturing stage through to end-of-life management.

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Acknowledgements

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Abbreviations and acronyms

ABS	acrylonitrile butadiene styrene
ALDFG	abandoned, lost or otherwise discarded fishing gear
B2B	business-to-business
CBMs	circular business models
CE	circular economy
CEN	European Committee for Standardization
CEWEP	Confederation of European Waste-to-Energy Plants
DFG	derelict fishing gear
EC	European Commission
EMFF	European Maritime and Fisheries Fund
EOLFG	end-of-life fishing gear
EPR	Extended Producer Responsibility
EU	European Union
EVA	ethylene-vinyl acetate
FAO	Food and Agriculture Organization of the United Nations
FAD	fish aggregating device
FMEA	failure mode and effects analysis
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GGGI	Global Ghost Gear Initiative
HDPE	high-density polyethylene
IUU	illegal, unreported and unregulated fishing
IMO	International Maritime Organization
ISO	International Organization for Standardization
KIMO	Kommunernes International Miljøorganisation *(Local Authorities International Environmental Organization)*
LDPE	low-density polyethylene
MARPOL	International Convention for the Prevention of Pollution from Ships
MSFD	Marine Strategy Framework Directive (2008/56/EC)
NIR	near infrared
NOAA	National Oceanic and Atmospheric Administration
NGO	non-governmental organization
OSPAR	Oslo-Paris Convention for the Protection and Conservation the North-East Atlantic and its Resources
P2P	peer-to-peer
PA	polyamide, also commonly referred to as Nylon
PE	polyethylene

PES	polyethersulfone
PET	polyethylene terephthalate
PP	polypropylene
PPC	polypropylene carbonate
PRF	Port Reception Facility
PRFD	Port Reception Facilities Directive
PS	polystyrene
PSW	Plastic Solid Waste
PU	polyurethane
PVC	polyvinyl chloride
RFID	radio-frequency identification
RFMO	regional fisheries management organization
SBMPL	sea-based marine plastic litter
SMEs	small and medium-sized enterprises
SUP	single-use plastic
SUPD	Single-Use Plastics Directive
UHF	ultra-high frequency
UHMWPE	ultra-high molecular weight polyethylene
UNCLOS	United Nations Convention on the Law of the Sea
VGMFG	Voluntary Guidelines on the Marking of Fishing Gear
WFD	Waste Framework Directive (Directive 2008/98/EC, 2008)

Technical terms

Abandoned, lost or otherwise discarded fishing gear (ALDFG)	"Abandoned fishing gear" means fishing gear over which an operator/owner has control, and which could be retrieved by that owner/operator but is deliberately left at sea as a result of force majeure or other unforeseen circumstances. "Lost fishing gear" means fishing gear over which the owner/operator has accidentally lost control and that cannot be located and/or retrieved by owner/operator. "Discarded fishing gear" means fishing gear that is released at sea without any attempt for further control or recovery by the owner/operator (FAO, 2019a).
Chemical recycling	The process of converting any plastic polymer into its original monomers, or the production of raw materials, by changing the chemical structure of plastic waste items, which can then be used in the production of new products (Manzuch *et al.*, 2021).
Circularity	The degree to which assets, components, subcomponents and materials are kept "circling" through value chains, without having a definitive conclusion (World Economic Forum, 2017).
Depolymerization	The process of converting a polymer into a monomer, a mixture of monomers, or a polymer of lower relative molecular mass (Jenkins *et al.*, 1996).
Downcycling	The phenomenon of quality reduction of materials reprocessed from waste, relative to their original quality (Helbig *et al.*, 2022).
End-of-life fishing gear	Fishing gear and gear accessories (e.g. ropes, floats, sink weights and other attachments) that are no longer actively used by fishers. These gears can be old, redundant, retired, disused, damaged or discarded (Stolte *et al.*, 2019).
Energy recovery	Burning (i.e. combusting, incinerating) waste to produce energy in the form of heat, steam and electricity (Al-Salem *et al.*, 2009). These processes are often referred to as "waste to energy" processes (Kothari *et al.*, 2011; Psomopoulos *et al.*, 2009). Energy recovery definitions vary across the literature (Mazzoni and Janajreh, 2017; Sharuddin *et al.*, 2018), with some definitions including thermal conversion processes for fuel (see 'Thermal conversion' below). This report employs the term "energy recovery" specifically in the context of quaternary recycling processes (see description below), through combustion. It distinguishes between thermal conversion processes that do not fully oxidize the waste feedstock to produce fuels.
Extrusion	A process where a material undergoes plastic deformation by the application of a force causing that material to flow through an orifice (Maier and Calafut, 1998).
Fine sorting	A labour-intensive sorting approach for recovered ALDFG and (sometimes) EOLFG intended for recycling, which involves the manual separation of all waste fractions (Schneider, 2020; Stolte *et al.*, 2018).

Fishing gear	Any physical device or part thereof or combination of items that may be placed on or in the water or on the seabed with the intended purpose of capturing or controlling for subsequent capture or harvesting of marine organisms, in accordance with MARPOL Annex V (FAO, 2018b).
Flue gas	The gas that emanates from combustion plants and which contains the reaction products of fuel and combustion air and residual substances such as particulate matter (dust), sulphur oxides, nitrogen oxides, and carbon monoxide (sometimes also referred to as exhaust gas) (Speight, 2019).
Gasification	An intermediate, two-step, endothermic process between pyrolysis and combustion. During the first step, the volatile components of the fuel source are vaporized at temperatures below 600 °C by a set of complex reactions without oxygen, with the creation of char (fixed carbon) and ash by-products. In the second step, the char is gasified through reactions with oxygen, steam, and hydrogen. Some of the unburned char is also combusted to release heat required for the endothermic gasification reactions (IEA, 2016).
Ghost fishing gear	The terms "ghost gear" or "ghost fishing gear" are often used synonymously with ALDFG. These are more nuanced terms, however, that relate to the impacts arising from ALDFG. Ghost gear is defined as ALDFG that has the ability to continue fishing after all control of that gear is lost by the fisher (GESAMP, 2021).
Marine litter	Any persistent, manufactured or processed solid material discarded, disposed of, abandoned or lost in the marine and coastal environment (also commonly referred to as marine debris) (UNEP, 2021a).
Mechanical recycling	Processing of plastic waste into secondary raw materials without significantly altering the chemical composition of the material (ISO, 2008; Plastics Europe, 2023). This is a mechanical (physical) process that typically includes processes such as sorting, washing, drying, grinding, melting, and re-granulating.
Monomer	A monomer molecule, which can undergo polymerization, thereby contributing constitutional units (e.g. atoms or groups of atoms) to the essential structure of a polymer molecule (macromolecule) (Jenkins *et al.*, 1996).
Passively fished waste	Waste collected in nets during fishing operations (Mannaart and Bentley, 2022).
Polymer	A molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass (Jenkins *et al.*, 1996).
Primary recycling	The process of mechanically reintroducing clean single-polymer plastic to the extrusion cycle in order to generate products of a similar material with properties equivalent to the original (Al-Salem *et al.*, 2009).

Pyrolysis	Thermal treatment that irreversibly and chemically decomposes organic wastes and polymers into liquid condensates (pyrolysis oil) and synthetic gases by heating dry input materials to 400-800 °C (Stolte et al., 2019). Pyrolysis is also often referred to as "thermal cracking" because of its use of heat under anoxic (i.e. no oxygen) conditions to convert plastic input materials into basic hydrocarbons; these can be converted to oils, light gases, and ashes (BPF, 2023; The Consumer Goods Forum, 2022).
Quaternary recycling	Energy recovered from waste plastic by incineration (Merrington, 2017).
Recycling	The conversion of waste resources into materials that may be used to replace virgin materials in new products, materials, or substances, for original or other purposes (Manzuch *et al.*, 2021).
Rough sorting	A sorting approach for recovered ALDFG and EOLFG intended for recycling that involves the removal of mostly large metal and other items (Stolte *et al.*, 2018).
Secondary recycling	Plastic solid waste materials are mechanically introduced to the extrusion cycle and reduced in size to more acceptable shapes and forms: these include pellets, flakes, or powders, depending on the input material quality and polymer composition. The materials produced are of an overall lower quality than the original materials introduced into the recycling process (Dorigato, 2021; Ragaert *et al.*, 2017).
Slag	Slag is formed during burning processes (i.e. combustion) and may contain heavy metals including aluminium, copper, zinc, and lead. Slags from incineration plants require additional processing for the recovery of valuable material components and to reduce negative environmental impacts arising from its storage (Kolodezhnaya *et al.*, 2019).
Steam reforming	A thermal process that converts organic substances or polymers into hydrogen-rich synthetic gases through evaporation, at temperatures over 1000° C. This method allows for up to 30 percent humidity in the material to be used in the conversion of waste products into synthetic gases (Stolte *et al.*, 2019).
Tertiary recycling	The processes to recover chemical constituents from polymer waste (Sahajwalla and Gaikwad, 2018). The production of fuels from polymer wastes is sometimes but not always included in definitions for tertiary recycling (Manzuch *et al.*, 2021; Merrington, 2017).

Thermal conversion	Alternative processes to incineration that do not fully oxidize the waste feedstock to allow for the production of products other than heat and power (which are often referred to as energy recovery processes, per the description above); these typically include liquid and gaseous fuels (IEA, 2022; Kunwar *et al.*, 2016). Thermal conversion includes a variety of thermal processes; those included in this report are pyrolysis (see pyrolysis description above) and gasification (see description of gasification above) (Goodship, 2007; IEA, 2022). These processes are sometimes grouped with energy recovery (i.e. waste to energy and incineration) processes (Awasthi *et al.*, 2019). This report includes thermal conversion processes through pyrolysis and gasification under tertiary processes, given that this is a more common categorization in the available literature (Manzuch *et al.*, 2021; Merrington, 2017). Some have advocated that these processes, when categorized under advanced/tertiary processes, should be referred to as "chemical recovery" or "thermal recovery" (Koyuncu *et al.*, 2021).
Unwanted fishing gear	Fishing gears that are no longer in use and no longer wanted for use, without any plans or potential for future fishing use (e.g. reuse by a different fisher). These include abandoned, lost or otherwise discarded fishing gear (ALDFG) and end-of-life fishing gear (EOLFG).
Upcycling	A process in which materials are converted into something of higher value and/or quality in their second life (Sung, 2015).
Waste	Any substance, material or object which is discarded after its primary use, or which is worthless, defective or no longer useful (Manzuch *et al.*, 2021).

Executive summary

Recycling end-of-life fishing gear (EOLFG) and recovered abandoned, lost or otherwise discarded fishing gear (ALDFG) can contribute to more sustainable fisheries. Recycling supports responsible fishing gear stewardship, preserves and prolongs the use of valuable gear materials and components, provides a valuable alternative to landfilling, and incentivizes the collection of EOLFG and recovery of ALDFG. Furthermore, it helps to conserve raw materials and energy resources by continuing the life cycle of the materials recycled, and thus reduces the demand for the creation of new materials.

The purpose of this report is to provide a background of the current state of knowledge around fishing gear recycling. The report examines fishing gear recycling technologies and practices, technical measures and policy/regulatory instruments that can support fishing gear recycling, and circular economy considerations for fishing gears. The topic of fishing gear recycling is a rapidly evolving field. As such, this report presents a snapshot of technologies today. It is intended for a broad range of audiences, from those unfamiliar with opportunities for fishing gear recycling, to those more engaged with the ALDFG/EOLFG issue and/or involved in the recycling sector and work to promote a circular economy approach to fishing gear management. This can include policy makers, managers, regulators, port authorities, researchers and non-governmental organizations, among others.

Part One of this report provides an overview of current **fishing gear recycling technologies and practices** and discusses the challenges and opportunities for the various fishing gear recycling options. The report covers primary and secondary (mechanical), tertiary (chemical recycling, chemical recovery and thermal conversion), and quaternary (energy recovery) recycling processes. The different processes allow for the recovery, treatment and recycling of a large variety of fishing gears, including their constituent materials and plastic polymers. The quality and diversity of materials that comprise unwanted fishing gears (i.e. ALDFG and EOLFG) introduce a range of challenges to their recyclability. Because ALDFG and, to a lesser extent, EOLFG, often include considerable amounts of organic and inorganic contaminants and pollutants from their use in the marine environment, recycling processes depend on the degree of contamination, as well as the degrees of polymer purity that comprise the gears.

Mechanical recycling (primary and secondary recycling) is typically adopted as the main method of fishing gear recycling, because of its ability to convert plastic materials into smaller components such as pellets and granulates, which can be recycled into different plastic products. This is a well-known and widely available technology for plastic waste processing, such as plastics used for packaging. Mechanical recycling is generally the most economical fishing gear recycling option, which consumes the least energy. However, several drawbacks often emerge from mechanical recycling of fishing gears, including the multistage, labour- and resource-intensive pre-processing requirements for fishing gears. This is in addition to the limitations around recycling contaminated and mixed polymer gears. Secondary recycling processes are also sometimes criticized as not being truly circular by virtue of the downgrading of the quality of the material produced.

Tertiary recycling (chemical recycling, chemical recovery and thermal conversion) methods can complement mechanical recycling through their ability to recycle fishing gears and constituent materials that cannot be recycled via mechanical processes, or to produce a higher-quality end product (e.g. through depolymerization, which also requires largely clean, single polymer inputs). Chemical recycling processes change the chemical structure of plastic waste items to recover constituent monomers and polymers, which can then be used in the creation of new products. Chemical recycling and thermal conversion processes are sometimes criticized as they can be expensive, **energy intensive**, and produce hazardous and toxic by-products that require stringent pollution controls. Thermal conversion processes, which are sometimes but not always included under tertiary recycling methods, produce liquid and gaseous fuels. Definitions for recycling for thermal conversion processes vary. In Europe, for example, fuel outputs from tertiary processes are excluded from chemical recycling definitions, with recycling restricted to the production of substances that are used as products or raw materials for the manufacturing of new products. In other regions such as North America, fuel outputs are included under advanced/enhanced recycling definitions.

For fishing gears that are too complicated or not possible to recycle using primary, secondary or tertiary recycling processes, **quaternary recycling** technologies, often referred to as "**energy recovery,**" can be employed. These technologies use incineration to convert unwanted fishing gears into heat and steam that can be recovered for use as energy. Given the high energy demands, expensive infrastructure requirements, and potential for the creation of pollution in the incineration processes, which therefore require stringent pollution controls, energy recovery should only be viewed as a fishing gear recycling option if primary, secondary and tertiary recycling processes are not possible.

A variety of **technical measures** are available to support fishing gear recycling. Key considerations at the **fishing gear design** stage can support improved gear recyclability, such as: minimizing the number of mixed polymers in gears; using clearly labelled single polymers; designing gears that are easier to disassemble; and avoiding hazardous and toxic materials that inhibit the ability to recycle gears and pose environmental and health concerns in the recycling process. Fishing gears can be marked to identify ownership and position, which facilitates gear recovery and return. **Marking** gears in this way supports improved gear stewardship so that they can be collected and available for recycling at their end of life. Gears can also be marked to identify their material composition, including polymer composition, which facilitates disassembly and recycling pre-treatment processes such as sorting. Dedicated EOLFG and recovered ALDFG **reception facilities at fishing ports** are also necessary to provide fishers with sites where they can deliver their unwanted gears, gear components and collected scraps from gear repairs for recycling. Following the collection of unwanted fishing gears at port reception facilities, gears can be prepared for recycling at centralized or decentralized waste treatment facilities, depending upon the volume of unwanted gears and location of local ports and recycling facilities.

While an analysis around the economic feasibility of the various recycling options presented was outside of the scope of this report, the report does discuss how **market-based instruments (MBIs)** can support fishing gear recycling, especially considering challenges for recycled plastic products to compete with new plastic products. Market-based instruments in the form of tools and technical measures, and including management policies and regulatory measures, can be used to influence the cost or market price of fishing gears and provide mechanisms to support recycling services financially. An MBI can be employed to incentivize and reward recyclable fishing gear designs, the return and collection of unwanted fishing gear for recycling, and raise revenues needed to support fishing gear recycling infrastructure. The MBIs that can be used to support fishing gear recycling, and discussed in this report, include fishing gear 'buy-back' programmes, deposit-refund schemes, registration and deposit systems, taxes and indirect port-waste fees. Extended Producer Responsibility (EPR) schemes can also be developed and implemented to finance and organize systematic fishing gear collection and recycling, and drive innovation in recyclable fishing gear design and end-of-life management. Such schemes make the fishing gear producers – including fishing gear manufacturers, assemblers, importers, distributors and retailers – responsible for the entire life cycle of the gears that they introduce into the market, as well as the collection and transport of gears at the end of their life for disposal and recycling.

The report also discusses **global and regional policy instruments** related to recovered ALDFG and EOLFG that include considerations around fishing gear recycling, whether directly or indirectly. Key global policy instruments summarized include, but are not limited to, a variety of United Nations conventions, protocols and voluntary agreements including by the Food and Agriculture Organization of the United Nations (FAO), the International Maritime Organization (IMO) and the United Nations Environment Programme (UNEP). At a regional level, relevant fishing gear policy instruments that directly or indirectly influence fishing gear recycling include regulatory and management decisions around EOLFG and ALDFG undertaken by regional management and policy organizations and bodies, including regional fisheries management organizations (RFMOs), regional fishery bodies (RFBs) and regional seas organizations and programmes.

The first part of the report concludes with discussion of the application of **circular economy (CE) principles to fishing gears**, including fishing gear recycling. The term CE refers to production and consumption models that aim to avoid waste and pollution from the beginning of, and throughout, a product's life cycle. This approach enables resources and materials to be reused and recycled back into product value chains as much as is practical, allowing them to retain their value and worth as long as possible. A CE model for fishing gears includes fishing gear recycling as one option in a larger suite of stages in the life cycle of fishing gear. Waste hierarchy and R-based (e.g. 3Rs) CE models and concepts are additionally discussed for fishing gear end-of-life management stages. In the fishing gear waste hierarchy, priority is given to waste avoidance and reduction, followed by the reuse, recycling, alternative recovery (including energy recovery), and disposal. This prioritization aims to optimize the use of resources and eliminate the need for final disposal (e.g. landfill).

Following the discussions of fishing gear recycling technologies and processes, technical and policy measures, and circular economy principles, the second part of the report presents **practical examples of fishing gear recycling** around the world. This includes examples of fishing gear recycling initiatives at local, national and regional scales, as well as examples of the repurposing of unwanted fishing gear, mechanical and chemical recycling and energy recovery. In addition, part two also highlights innovative products made from recycled fishing gears. It ends with an example of a regional initiative that aims to support the development of the circular economy for fishing gear.

The circular economy and waste-hierarchy principles highlighted in this report can better inform the full life cycle of fishing gears from the design stage to their end-of-life management. The different fishing gear recycling technologies, together with the technical measures and policy instruments summarized, provide background on the varying options for fishing gear recycling around the world. The range and diversity of gear types in use globally and locally demand differing national and regional capacities to support fishing gear recycling. Both in technological terms and through effective waste management systems and frameworks, different gears ultimately necessitate a combination of recycling measures and complementary interventions that are tailored to the requirements and capacities of each country, region, locality and their associated fishing techniques.

Part I – Fishing gear recycling methods, technical measures, policy instruments and circular economy considerations

1. Fishing gear recycling methods, technical measures, policy instruments and circular economy considerations

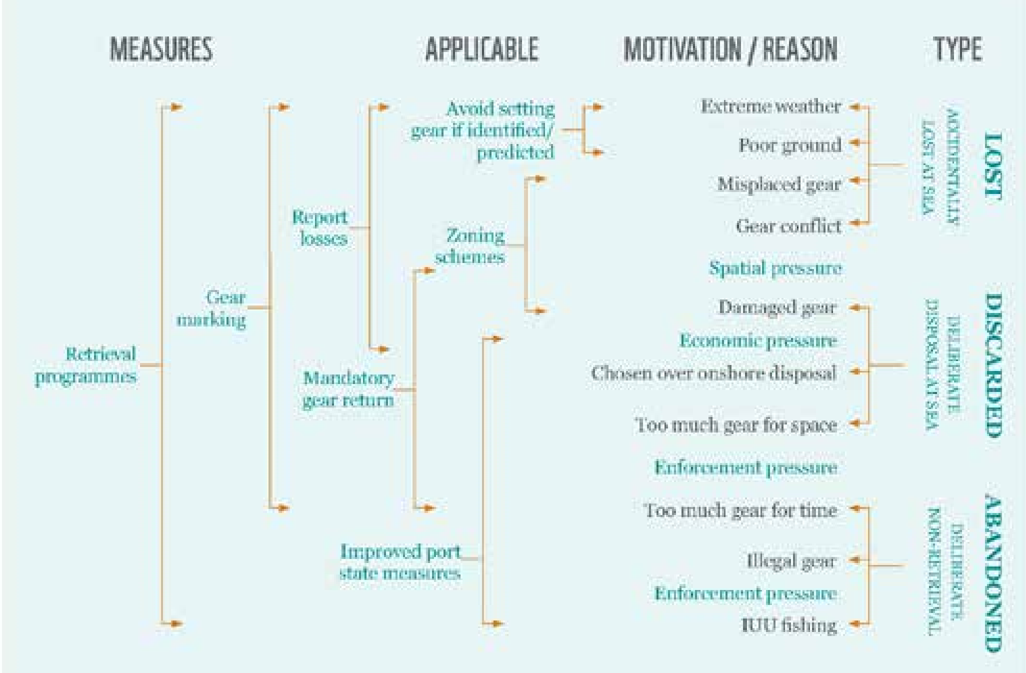
1.1 INTRODUCTION

The increase of marine plastic litter over the last half century has exacerbated pressures from a growing list of environmental stressors, including climate change and overfishing (FAO, 2020; Lebreton *et al.*, 2018). While it is broadly recognized that most global marine plastic litter originates from land-based sources, sea-based sources including fisheries, shipping, dredging and offshore oil and gas activities among others, introduce substantial amounts of litter into the world's oceans. FAO (2021) reported an annual use of 2.1 million tonnes of plastic products in the fisheries and aquaculture industries. Although it is not known what proportion of this total quantity results in marine litter, the most widely recognized problematic plastic waste category produced by the fishing sector is unwanted fishing gear. Unwanted fishing gear is often generally referred to and categorized either as end-of-life fishing gear (EOLFG) or as abandoned, lost or otherwise discarded fishing gear (ALDFG).

According to FAO's *Voluntary Guidelines on the Marking of Fishing Gear* (VGMFG) (FAO, 2019a), "Abandoned fishing gear" means gear over which the operator/owner has control and which could be retrieved by the owner/operator, but is deliberately left at sea because of force majeure or other unforeseen reasons. "Lost fishing gear" means fishing gear over which the owner/operator has accidentally lost control and that cannot be located and/or retrieved by owner/operator; while "Discarded fishing gear" means fishing gear that is released at sea without any attempt for further control or recovery by the owner/operator (FAO, 2019a).

Abandoned, lost or otherwise discarded fishing gear (ALDFG), which is also often referred to as "ghost gear," is therefore a significant source of marine litter, with serious negative environmental and socioeconomic impacts on marine and coastal habitats, fish stocks and other marine species. It also poses navigational risks and risks to safety at sea (Macfadyen *et al.*, 2009). According to Richardson *et al.* (2022), nearly 2 percent of all fishing gear enters the world's oceans each year; this amounts to more than 25 million pots and traps, 75 049 km^2 of purse seine nets, 218 km^2 of trawl nets, and 739 583 km of longline mainlines. Estimates of the quantity of ALDFG entering the ocean each year, as well as its causes, are helpful for developing and implementing management interventions and solutions aimed at reducing gear losses (Richardson *et al.*, 2021; Stöfen-O'Brien *et al.*, 2022). Figure 1 summarizes the primary causes of ALDFG, alongside associated prevention, mitigation and recovery measures.

FIGURE 1. ABANDONED, LOST OR OTHERWISE DISCARDED FISHING GEAR (ALDFG) CATEGORIES, CAUSES AND POTENTIAL MEASURES TO ADDRESS IT



Source: Modified and adapted from WWF (2020). Ghost Gear Legislation analysis. Report by Ocean Outcomes, Global Ghost Gear Initiative (GGGI), and World Wide Fund (WWF) for Nature.

While fishing gears can be abandoned, lost or discarded to the ocean with a wide variety of adverse environmental and socioeconomic impacts, fishing gears are also often delivered to ports when wear, ageing and damage render these gears unusable. These gears are more generally referred to as "end-of-life fishing gear" (EOLFG), and are generally collected by fishers, fishing enterprises or cooperatives and disposed of in regular waste management systems. For example, they can be disposed of in a recycling bin, a dumpster, and then delivered to a landfill or incineration plant along with other household or commercial waste. In some cases, they can be deposited in dedicated EOLFG containers. If waste disposal infrastructure is present, the responsible disposal of EOLFG at ports can prevent unwanted fishing gears from being abandoned, lost or discarded at sea. However, ports and municipalities often do not have dedicated disposal systems for fishing gear; this can act as a disincentive for fishers to find responsible and alternative means for their unwanted gear disposal outside of landfill (Bertling and Nühlen, 2019).

Disposing of ALDFG and EOLFG in landfill, open burning or waste incineration without energy recovery results in the loss of valuable resources that could otherwise be recovered, as well as health and environmental hazards such as the toxic fumes produced from open burning (UNEP, 2021b). Recycling these recovered gears can reduce and mitigate their many environmental and socioeconomic impacts. However, according to Stolte *et al.* (2019), the extensive recycling of ALDFG is currently nearly impossible. Two factors are particularly important: 1) inadequate quality of materials to be recycled owing to contamination and 2) lack of single-polymer purity because of the combinations of multiple materials. What is more, ALDFG requires the manual removal of litter, organic contaminants, sediments and other materials entangled in the fishing gear before it can be processed for recycling, which is time-consuming and often expensive. A general lack of knowledge around the material and polymer composition of fishing gear and its properties results in additional challenges to the efficient recycling of ALDFG, and, to a lesser extent, the recycling of EOLFG.

Compared to ALDFG, EOLFG is less difficult to recycle because of overall lower levels of contamination and smaller proportions of mixed and entangled gears and gear components, with simpler preparation and processing requirements (Stolte *et al.*, 2019). Because of this, the vast majority of fishing gear recycling companies almost exclusively recycle EOLFG. Section 1.2.5 discusses opportunities and challenges for EOLFG and ALDFG recycling including considerations around gear design, materials and available technologies.

1.2 FISHING GEAR RECYCLING

One of the main goals of this report is to investigate practical methods for fishing gear recycling. This section synthesizes information around a variety of technologies and processes available to recycle fishing gears. It includes considerations for the recyclability of fishing gear materials in the design and manufacturing stages, through to collection and preparation for recycling at the end of the gear's life. With this in mind, the physical and chemical characteristics of unwanted fishing gears are examined, alongside discussion of how these characteristics affect their recycling potential. Requirements for the preparation of unwanted fishing gear for recycling processes are also discussed, including collection, sorting, disassembly, cleaning and cutting/shredding/grinding. This section ends with a discussion of the opportunities and challenges presented by these technologies and processes, as well as the circumstances under which one recycling method may be better suited compared to others.

1.2.1 Fishing gear design and manufacturing

Fishing gear is designed and manufactured with high-strength materials that contain valuable mechanical and physical properties required to catch and ensnare target species. A large variety and often a combination of different materials can be used in the construction of fishing gears, which include a diversity of plastic polymers, metals (largely lead and steel), wood and natural twines and fibres (see Section 1.2.2).

According to Charter *et al.* (2020), important considerations for fishing gear product design and development include:

- Functionality: Gears should include species-specific designs that are appropriate for aquatic environment conditions; the fishing methods employed should also be considered while designing equipment.
- Customization: Gear should be designed to fit the fishing technique and operator activity. See Table 1 and the Classification and illustrated definition of fishing gears (He *et al.*, 2021) for more detailed information on gear classification including common types, components, materials and structure.
- Choice of material and durability: Fishing equipment must endure tough marine and aquatic conditions. Therefore, nylon, polypropylene, and polyethylene polymers are frequently braided or twisted to increase material strength in the construction of fishing nets and ropes. Newer plastic materials, like those employing ultra-high molecular weight polyethylene (UHMWPE) (e.g. Dyneema®), can prolong the longevity of fishing nets and ropes and are often used in gears to boost fishing productivity and efficiency; these include lower fuel consumption and energy costs on fishing boats through reduced drag and enhanced durability in the marine environment. At the end of their useful lives, these sophisticated technological materials can present recycling challenges, notably because of the UHMWPE fibre. The polymer structure of UHMWPE changes at low temperatures, which results in unusable extruded products (i.e. mechanical recycling, see Section 1.2.4.1) and necessitates chemical recycling processes (see Section 1.2.4.2).

- Failure mechanisms: Gear failures can result from gear straining and shearing. While design for durability is important, gears should also be designed to prevent, to the extent possible, known failure from controllable and sometimes external circumstances such as overload, stress and damage. In the event that gears are abandoned, lost or discarded, they can also be designed with mechanisms to prevent, reduce and minimize impacts from ghost fishing – the gear's ability to continue to catch and ensnare target and non-target species after becoming ALDFG – such as the incorporation of biodegradable gear components into pot/trap escape mechanisms.
- Inclusion of specialized materials and components: Examples include metals which can be designed into fishing gears when a rigid and especially strong construction is required, such as with traps, hooks, and weights. Fishing gear may also include extra components like acoustic deterrents that release sounds to scare away larger non-target fish, or mammals who may become entangled in and cause damage to the gear. Copper-based and other biotoxin antifouling coatings are sometimes added to nets and ropes, particularly in aquaculture operations (Basurko *et al.*, 2023).

Discussions with fishing gear manufacturers revealed that formal product design and development training, tools, and methodologies are less frequently used in the fishing gear industry compared to other manufacturing sectors (Charter *et al.*, 2020). Fishing gear producers also frequently do not formalize or make their product design and development processes publicly available, as they are often based on individual expert knowledge and experience and contain important intellectual property protections. This results in large knowledge gaps around the material composition of fishing gears, including the selection and mixture of different polymers and additives, which complicates the ability to recycle these gears efficiently at their end of life.

The often-complex mixtures of materials and polymers in fishing gears required to account for the design considerations outlined above, as well as the lack of publicly available information around material and polymer composition of gears from designers and manufacturers, can complicate the eventual recyclability of fishing gears at the end of their life. Section 1.2.2 discusses the variety of recyclable materials present in unwanted fishing gears, including challenges and barriers to recycling that result from these complex material and polymer mixes. Section 1.3.1 discusses design opportunities and strategies to overcome these challenges and barriers, in order to improve gear recyclability.

1.2.2 Recyclable fishing gear materials

Until the 1960s, fishing equipment was mostly made of metals, wood, and natural fibres (e.g. linen, hemp, cotton), which degrade in aquatic environments (Andrady, 2015). Invented a little more than a century ago, plastics are now the most widely used material in fisheries operations because of the evident advantage in terms of versatility, strength and lifetime, in addition to an industry-wide switch to plastic gears (Feary *et al.*, 2020).

A variety of plastic polymers are used in fishing equipment. The main raw polymer types utilized to manufacture the majority of fishing nets include nylon or polyamide (PA) (including aromatic polyamide or aramid), low-density and high-density polyethylene (LDPE and HDPE), polyethylene terephthalate (PET) (often in the form of polyester (PES), and polypropylene (PP). However, most modern fishing nets can be composed of hundreds of different combinations of these polymers and other materials. Ropes are often composed of PP or PES. Floats and buoys, bait boxes, and food service equipment are often made from polystyrene (PS) and sometimes polyurethane (PU), with many floats and buoys also often made from PET (Feary *et al.*, 2020). Other, harder polymers are also employed in gears and gear attachments, such as HDPE, which is used in dredges, aquaculture cages and some fishing nets. Some gears can also include natural, non-synthetic materials including wood, natural fibres and organic cottons (e.g. wooden lobster traps, natural fibres in fish aggregating devices [FADs], cotton twine used for biodegradable escape mechanisms in some pot/trap fisheries). In some cases important gear components such as nets and ropes can be treated with copper-based and other biotoxin antifouling coatings (Basurko *et al.*, 2023), which complicates and sometimes prohibits recycling and other environmentally sound repurposing or disposal methods. Table 1 outlines common fishing gear components and material composition by major gear type.

TABLE 1. COMMON FISHING GEAR COMPONENTS AND MATERIALS BY MAJOR GEAR TYPE

Gear Type	Gear Structure	Gear Materials Composition
Surrounding nets - Purse seines - Surrounding nets without purse lines	Bag or purse-shaped net with a codend, bunt or "harvest" section; edges defined by a purse line with a purse string; float line with floats; sinker line; pulling lines	Netting: woven polymer fibres, e.g. PA/nylon, PES Lines: polymer fibres, e.g. PP, PE, UHMWPE, PA Floats: PVC, EVA; Sinkers: lead; Purse rings: iron or brass
Seine nets - Beach seines (SB) - Boat seines (SV)	Long-walled nets with floating and sinking lines, may or may not have a codend (bunt)	Netting: PE, PA Floating lines: PP/PE/PA with PVC/ABS floats Sinking lines: same as above with leads or other weights
Trawl nets - Beam trawls - Bottom trawls - Midwater trawls	Net top, bottom and side panels and a codend (bunt), with a float (head) line and sinking (footrope) line, bridle/sweep lines, and warp for towing, +/- otter boards	Netting: woven polymer fibres of PA/nylon, PE, occasionally UHMWPE Lines: PP/PA/UHMWPE Sinking lines: same as above with rubber, ABS or metal blocks Otter boards: steel, wood beam: metal, wood, bamboo
Dredge nets - Towed dredges (Mechanized dredges, hand dredges)	Metal frame with "cutting bar" on bottom edge and net or chain bag attached; mechanized dredges include a high-pressure hydraulic pump; hand dredges (artisanal) typically employ a pole leading to a metal frame with a mesh bag with teeth on its lower edge	Netting: PE or chain metal Frame and cutting bar: iron
Lift nets - Lift nets (portable, stationary, boat-operated, shore-operated)	Netting, lift lines and sinking lines, lateral poles	Netting: PE/PA fibre Lift lines: PA/PP fibre Sinking lines: same as lift lines with lead blocks Poles: natural, PVC/ABS, or metal
Falling gears - Falling gears (cast nets, lantern nets)	Netting attached to hand or brail lines, and sinking line	Netting: PA/PES fibres Sinking line: PVC/ABS with lead blocks
Gillnets and entangling nets - Gillnets (set, drift, encircling) - Entangling nets (trammel nets)	Single or three-walled netting; floating (head) lines and sinking (footrope) lines, buoys, +/- anchors (for set gillnets)	Netting: monofilament nylon (PA) or woven fibres comprised of PES, nylon or PE; Headline: PP/PE with PVC/EVA/ABS/expanded PS floats; Sinking lines: PP or PES with lead blocks or lead core Buoys: vinyl/PVC/PUR
Traps - Large stationary nets or barrages	Netting; floating (head) line and sinking (ground) line; beams or T-frames for spreading net; anchors and buoys.	Netting: woven polymer fibres, typically PE Float and sink lines: PP/PA with PVC/EVA floats and lead sinkers; T-frames or beams: "plastic" or steel pipes, or natural materials (e.g. wood, bamboo); Buoys: PVC /PUR/vinyl; Anchor: iron
Pots	Pots are typically metal or wooden frames with synthetic or wire mesh	Pot: PVC coated wire, wood, PE netting Rope: PP; Anchor: iron
Hooks and Lines - Pole-and-lines (handlines, hand-operated, mechanized, trolling, and vertical lines) - Longline (set and drifting longlines)	Main line, branch lines, hooks, lures, floats and sinkers	Main lines and branch line: PP/PA multifilament, PA monofilament; Hooks: steel; Lures: metal, PVC, rubber Floats: PVC Sinkers: lead

Notes: major gear type are classified according to the FAO *International Standard Statistical Classification of Fishing Gear* (FAO-ISSCFG) (FAO, 2010, 2016a; He *et al.*, 2021; Nédelec and Prado, 1990).
Source: Modified and adapted from GESAMP (2021). Sea-based sources of marine litter. In: Gilardi, K., ed. IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, GESAMP Working Group 43, 2021. Report and Studies No 108 (http://www.gesamp.org/publications/sea-based-sources-of-marine-litter).

Many of the synthetic polymers such as PP, PE, and PA found in fishing gears represent high-value polymers on the recycling market. Both EOLFG and recovered ALDFG can be reintroduced into the manufacturing cycle as valuable raw materials when effective separation and cleaning procedures are employed (see Section 1.2.3). For example, nylon (PA) can be recycled into textile fibres and carpet materials, and PP/PE can be recycled into pallets and other household items such as buckets and trays (Wong, 2022).

However, the variety of materials and polymer mixtures present in fishing gears often complicates recycling efforts because of the need to separate different types of material, notably different plastic polymers which make up a single gear component. This is true of mechanical recycling and some chemical recycling processes, and can create the need for more complex and expensive processes such as chemical recovery, thermal conversion and incineration.

1.2.3 Preparing fishing gears for recycling

Both ALDFG and EOLFG require sorting and manual processing operations and facilities to prepare them to be recycled (Stolte *et al.*, 2019); this is especially true of nets, ropes and traps, which often have many attached and component parts. Moreover, the typically very high contamination levels in recovered ALDFG (compared to EOLFG) significantly affect the pre-recycling treatment process. Mixtures of salt, sand, stones, wood, fabrics, marine biota, and other adsorbed pollutants and wastes can contaminate fishing gear after extended periods in saltwater (Van Meel, 2022). If fishers are encouraged to recover ALDFG found at sea, a waste management pathway for the retrieved materials must be established that is capable of handling the presence of mixed polymers, biological substances, marine litter, metal objects, and rocks and lead contamination. The waste management pathway should also be able to manage the separation of harmful and toxic portions of recovered gears, and shred large batches of mixed materials without causing damage to available equipment. As a result, ALDFG recycling requires a multistage, cost-intensive treatment process that includes the manual sorting and cleaning of contaminants, as well as the separation of different plastics. Given these varied pre-processing challenges, recovered ALDFG is often better suited to some tertiary recycling processes such as steam reforming (see Annex 1.2), as well as other energy recovery processes (see Section 1.2.4.3), as opposed to mechanical recycling processes (see Section 1.2.4.1).

By contrast, EOLFG is much more widely available for recycling and requires less pre-processing compared to ALDFG. For example, Bertling and Nühlen (2019) estimated an annual recycling ratio of 1:3 for ALDFG to EOLFG in the Baltic Sea region, in their examination of recycling for these unwanted gears. As EOLFG is typically in use until the day it is disposed of, it often contains lower amounts of contaminants including salt, sediments and organic matter compared to ALDFG. While cleaning is still required, it is typically less labour-intensive than ALDFG.

The choice to collect EOLFG and ALDFG with other waste items is based not only on the quantity of material but also the recycling technique selected. Separate collection is recommended for mechanical (primary and secondary recycling) and chemical (tertiary) recycling to minimize contamination and tangling, and to avoid making future processing excessively onerous. In some cases, however, if total comparative volumes of ALDFG to EOLFG are small enough and ALDFG materials are pre-processed to allow for subsequent recycling, then these gears can sometimes be processed mechanically alongside one another. For example, it was estimated that ALDFG accounted for less than 1 percent of total fishing gear collected annually in a municipality in Sweden, with the remaining fishing gears representing EOLFG (Stolte *et al.*, 2019). As the volume of "good material" from the EOLFG (i.e. material readily available for recycling, such as compatible or unmixed polymers and uncontaminated materials) was so much greater than the mixed-material volumes from the ALDFG, it was determined that the ALDFG could be processed alongside the EOLFG. Furthermore, EOLFG and/or ALDFG can generally be collected along with residual litter in the event of energy recovery in incineration facilities, as this process does not require the polymer-grade purities, or lack of contamination (Bertling and Nühlen, 2019).

Recycling pre-processing procedures can vary according to the fishing gear type and recycling method, the resources available (personnel, tools and infrastructure) and the condition of the fishing gear. Pre-processing procedures largely involve: the sorting, disassembly and cleaning of gear items (particularly where sediments, biofouling and other contamination may be present); polymer type separation (e.g. PA, PP, PE, and PET must all be differentiated); the removal of lead lines, where present, to avoid harmful contamination; and the cutting and/or shredding of net materials into acceptable sizes for subsequent processing (Stolte *et al.*, 2019).[1] Each of these pre-processing procedures is examined in greater detail in Section 1.2.4.1.

Because ALDFG and EOLFG have been exposed to saltwater for long periods of time, they also require washing to reduce the salt content and any residual/accumulated sediments prior to the processing steps required for recycling. Pressure cleaners or composting can be used to clean ALDFG and more heavily contaminated EOLFG (Stolte *et al.*, 2019). Before further processing, fishers can let ALDFG compost in barrels to eliminate organic impurities such algae, seagrass, and marine biota (Stolte *et al.*, 2019). Composting is a simple and inexpensive way to remove organic materials before fishing gears are processed further for recycling. However, barrels and space must be made accessible in sections of the harbour where the composting emissions do not disturb harbour users. In the case of EOLFG and for some recovered ALDFG items, these gears can also be cleaned at sea before being brought to land. Proper storage and a timely shipment to the appropriate recycler are important for returned EOLFG, in order to avoid contamination from the sand and dirt that can penetrate into fishing gear fibres while ashore, as well as UV radiation that can degrade fishing gear fibres.

The fishing gear type being prepared for recycling will also influence the recycling method employed, and the associated pre-processing procedures required by the recycling infrastructure. For example, gillnets can be a particularly complicated gear type to recycle mechanically given the requirements to remove lead lines and sink weights, the need to separate different material types manually, and to separate higher- and lower-density polymers (Stolte *et al.*, 2018). During the cleaning process, fine polyamide fibres used in woven gillnet netting tend to fluff up and form conglomerates with other substances such as polypropylene (PP) and polyethylene (PE) fragments, as well as residual organic waste materials that were not eliminated during the cleaning stage. These materials are difficult to homogenize, and only a few mechanical recycling extruder settings allow these fluffy "fibre balls" to be used as incoming material (Stolte *et al.*, 2019).[2] Under these circumstances, gillnets are often considered better candidates for thermal processing due to lower pre-processing requirements and technologies that can handle the mixed polymers found in many gillnets more effectively. Other polymers comprising gears and gear components can be relatively simpler to prepare for recycling. One example is polyamide, particularly polyamide-6 (PA6) ropes, which are readily shredded after pre-sorting; their washable rope fibres produce an extremely clean textile that resembles raw wool in look and feel (Bertling and Nühlen, 2019). Not

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1 Previous studies have found many recyclers require net and rope pieces to be cut into 50 cm pieces or shredded to 2–4 cm fibre lengths (Stolte *et al.*, 2019).

2 The discussion around the cutting and shredding stage under the Pre-treatment stage for unwanted fishing gears in Section 1.2.4.1 mentions how guillotine cutters can result in less fluffing of gillnet fibres compared to industrial shredders.

only the differential requirements of the individual gear types, but also the polymer composition and degree of contamination will determine which recycling path should be undertaken and what degree of preparation is needed (further detail about these are included in Section 1.2.4).

Some examples of steps to prepare different gears for recycling are summarized below, based on Stolte *et al.* (2019):

- Traps: to reduce transit volume, traps can be squeezed with a hydraulic press. Any plastic netting used in traps can be melted to recover the metal for recycling. Where recycling facilities are not able to separate compacted materials, segregation can also happen prior to compaction to facilitate the recyclability of different gear materials.
- Gillnets: can be cut into 1-2 m portions (to facilitate transport and processing), with lead lines removed. Clean gillnets may be shipped to specialized companies for recycling, including mechanical recycling and depolymerization into yarns.[3]
- Trawl nets: are made from a variety of materials that can be separated during disassembly. Netting should be cut into sections/pieces to facilitate transport and processing.
- Attachment and component materials such as floats, wires, ropes, sink lines and weights can often be retrieved and reused. In comparison, because mesh widths and fibre sturdiness in fishing nets diminish with time and exposure to the sea environment, netting materials typically cannot be reused.

Education and training for the relevant personnel involved in preparing fishing gears for recycling can help ensure more efficient sorting of the different gears for the appropriate recycling pre-treatment stages by identifying a gear's material characteristics, including basic polymer types present. Involving fishers, as well as gear producers and vendors in these education and training initiatives can improve the quality of sorting given their knowledge and expertise of the materials.

Technologies are also available to assist with polymer identification in fishing gears. For example, innovations are available that use Raman spectroscopy to identify the different polymer compositions of fishing gears (Horiba Scientific, 2023a). Raman spectroscopy is a type of chemical analysis that uses light scattering techniques from lasers to interact with a material's chemical bonds and provide information about the chemical structure and composition of different materials (Horiba Scientific, 2023b). This technology can distinguish between different polymer classes (e.g. polyethylene and nylon) as well as polymers within a polymer class (e.g. Nylon 6 and Nylon 6,6) (Horiba Scientific, 2023a) that cannot be recycled mechanically in the same waste stream because of their different physical properties. Near-infrared (NIR) spectroscopy can also be employed to analyse materials on a molecular level and thus identify different polymer types. For example, the company trinamiX's NIR spectrometers can detect a broad range of polymer types and share results on a mobile app that is backed-up by cloud data; these technologies have been used in Alaska and the Gulf of Carpentaria to identify polymer types in ALDFG (Hardman, 2021; trinamiX GmBH, 2023).

Stolte *et al.* (2019) also documented the types of assistance necessary to support the preparation of unwanted fishing gears for recycling. These include:

[3] For example, Bureo's Net Positiva initiative mechanically recycles gillnets into granulates for hard plastic applications such as skateboards and sunglasses. At the time of this report, Aquafil is the only known company to be depolymerizing gillnets on an industrial scale. An example of a smaller-scale initiative includes the company Popsicase in Barcelona, Spain who is depolymerizing gillnets to produce phone cases.

a) **Education around unwanted fishing gear material characteristics,** including recognizing the basic polymer types and identifying fishing gears that can be pre-processed for mechanical recycling (primary and secondary recycling) compared to those gears that are too contaminated and require more advanced recycling processes (including tertiary and quaternary recycling).
b) **Financial support for pre-processing equipment** for unwanted fishing gears. This includes, for example, cutting tools and small-scale shredding facilities, and covered storage facilities at collection points to avoid rain/moisture absorption into the gears collected. Other financial support for recycling pre-processing activities includes staff costs, including to load materials for shipping, and transport costs to move the fishing gear materials from collection points to recycling facilities.
c) **Metal-specific collection point,** with safety measures for lead, particularly; and
d) **Cleaning tools that can support the recycling of larger material fractions,** such as pressure washers and composting sites.

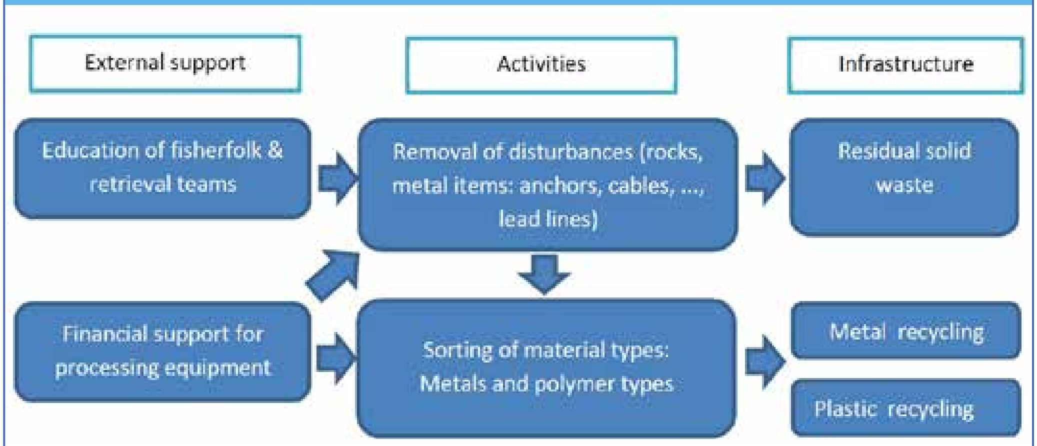
Figure 2 summarizes pre-processing requirements for recycling unwanted fishing gears.

1.2.4 Methods for recycling fishing gears

Plastic solid waste (PSW) production, consumption, and litter creation have all risen dramatically since the first industrial-scale synthesis of synthetic polymers (plastics) in the 1940s (Zia *et al.*, 2007). Decades of PSW research, analysis, and testing have yielded a range of economically and environmentally effective options for PSW treatment, recycling, and recovery processes (Al-Salem *et al.*, 2009).

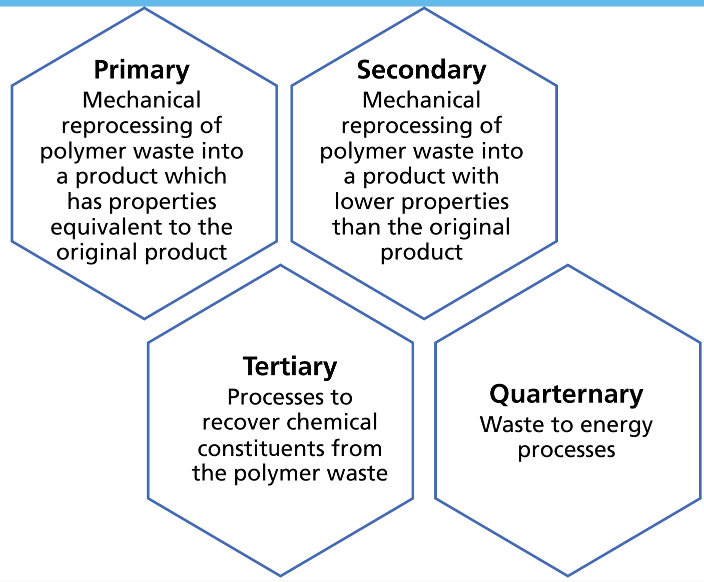
This section of the report summarizes the technical feasibility of the four main options for solid waste recycling treatments, with a special emphasis on plastic waste generated from unwanted fishing gear. The four main recycling processes summarized include primary and secondary (mechanical), tertiary (chemical) and quaternary (energy recovery) recycling schemes and technologies (Figure 3). Wherever possible, these processes are discussed in the context of unwanted fishing gears, given that almost all components of fishing gear as a multi-material product, including metals and other non-plastic materials, can be recycled using the appropriate available technology.

FIGURE 2. REQUIREMENTS AND PRE-PROCESSING PATHWAY OF UNWANTED FISHING GEAR IN PREPARATION FOR WASTE MANAGEMENT AND RECYCLING



Source: Modified and adapted from Stolte *et al.* (2019). A treatment scheme for derelict fishing gear. Interreg Baltic Sea Region Programme 2014–2020, MARELITT Baltic Project report (https://marelittbaltic.eu/documents).

FIGURE 3. CURRENT WASTE PLASTIC RECYCLING TECHNOLOGIES



Source: Modified and adapted from Sahajwalla and Gaikwad (2018). The present and future of e-waste plastics recycling. Current Opinion in Green and Sustainable Chemistry, 13, 102–107 (https://doi.org/10.1016/j.cogsc.2018.06.006).

1.2.4.1 Primary and secondary recycling (mechanical recycling)

Mechanical recycling processes are organized into primary and secondary recycling processes. **Primary recycling** is the process of mechanically reintroducing clean single-polymer plastic to the extrusion cycle, to generate similar material products with properties equivalent to the original product. This is often referred to as "closed-loop recycling" (Al-Salem *et al.*, 2009). Because of the requirements for clean (non-contaminated), single-polymer input materials, primary recycling is often employed for waste materials that are produced in the manufacturing process (Hillier *et al.*, 2022). Unused scrap produced in the manufacturing process can be ground up and reintroduced into the extruder, in a process that is known as re-extrusion. Scrap materials from fishing gear obtained in the manufacturing process could be a useful source of such materials, providing they are clean and made of a single polymer. Extracted gillnet netting of pure PA6 that has been sufficiently washed is another example of an unwanted fishing gear type that can be re-extruded. A combination of primary and secondary recycling might also be appropriate in the case of fishing net repairs. For example, the pieces of unwanted new materials used in net mending could be suitable for primary recycling, whereas the recovered cuttings from the nets under repair could be suitable for secondary recycling.

In **secondary recycling**, plastic solid waste (PSW) materials are mechanically introduced to the extrusion cycle and reduced in size to more acceptable shapes and forms such as pellets, flakes or powders, depending on the input material quality and polymer composition. The materials produced are of an overall lower quality than those introduced to the recycling process and are sometimes referred to as "downgrading" or "downcycling" processes (Dorigato, 2021; Ragaert *et al.*, 2017).

In primary and secondary recycling, the mechanical plastic recycling process begins with plastic components being melted (plasticized), and then processed into formed secondary raw materials, which are referred to as (re-)granulates, or plastic pellets. The polymer melt must be of a high-enough purity to produce a quality secondary raw material that is close to virgin plastic quality in order to allow for subsequent processing into the final product. A contaminated melt, and/or polymer combinations that are comprised of various melting temperatures and characteristics, can cause material instabilities and fractures in the final recycled material produced. When multiple plastic polymer types are mixed together in the input materials, secondary recycling can only be undertaken through a material downgrading process that produces lower-quality plastic outputs. As a result, the identification and appropriate separation of fishing gear polymers can greatly facilitate and improve the quality of recycled products produced.

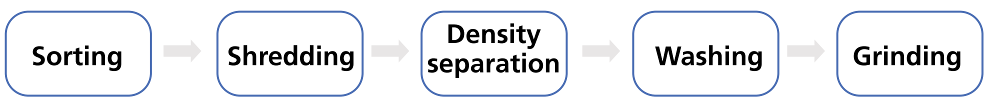
Mechanical recycling success is more probable if the polymers being recycled are isolated single polymers, or known compatible polymer mixtures, rather than unknown or incompatible polymer mixtures. For example, while PA is generally limited to compatibility with PS mixtures, it is also compatible with PET in small quantities for further processing in the melting process. However, PA is incompatible with PE and PP because they melt at much lower temperatures (Bertling and Nühlen, 2019). In light of these requirements for often high-quality and sometimes pure polymer inputs, plastic recyclers use integrated or separate melt filtering technologies to eliminate polymer contaminants (Bertling and Nühlen, 2019).

Specific pre-treatment processes for unwanted fishing gear prior to mechanical recycling

Unwanted fishing gear recycling requires a pre-treatment stage to allow for further automated processing under mechanical recycling processes. This stage typically involves sorting, cleaning, cutting/shredding/granulation, density separation (mostly for ALDFG), and washing and grinding (Figure 4).

The aim of the initial **sorting** process is to understand the material composition of fishing gears and remove large metal pieces and other large gear components, as well as sediments and organic material that would otherwise damage the shredding machines and contaminate the material being recycled. Sorting can be conducted with different levels of manual effort. The most labour-intensive sorting approach is "fine sorting" because it involves the manual separation of all waste fractions. The labour-intensive resource requirements for fine sorting – including associated time, availability and costs – results in it generally being considered unsuitable for large-scale operations (Stolte *et al.*, 2018). By contrast, "rough sorting" focuses on the removal of mostly large metal and other items and is the least labour-intensive sorting approach. Tests conducted during the MARELITT Baltic European INTERREG project determined that fine sorting required approximately 1 person-hour to sort 20–30 kg of recovered ALDFG materials composed of metal, ropes, nets, cables, wood and textiles (Stolte *et al.*, 2018).[4] The rough-sorting process was much faster, only requiring 1 person-hour to process 260-550 kg of recovered ALDFG materials (Stolte *et al.*, 2018). However, the rough-sorting process resulted in increased impurities in the desired net and rope materials for recycling because mussels, wood and other finer contaminants were ultimately not removed, and subsequent processing steps needed to cope with higher degrees of material contamination. The high number of residual metal and other contaminants from rough sorting may cause problems during the shredding step, resulting in rapid

FIGURE 4. SCHEMATIC OVERVIEW OF THE PRE-TREATMENT PROCESSES FOR UNWANTED FISHING GEAR



Source: Modified and adapted from Stolte *et al.* (2018). Recycling options for derelict fishing gear. Interreg Baltic Sea Region Programme 2014–2020, Project report (https://marelittbaltic.eu/documents).

[4] The sorting process was conducted by skilled persons, notably industrial recycling facility workers. However, these workers were not trained specifically to work with fishing gear. Involving fishers in the sorting process, as well as ensuring education and training for personnel undertaking it, will ensure more efficient sorting of recovered ALDFG and EOLFG at the pre-treatment stage.

wear of the cutting edges. Preliminary ALDFG assessment and cleaning efforts at harbours by fishers can facilitate the sorting process and help to reduce or eliminate the gear-cleaning processes: for example, by dumping nets into the water numerous times before lifting the material on board, or stretching nets out and pre-cleaning them upon return to port.

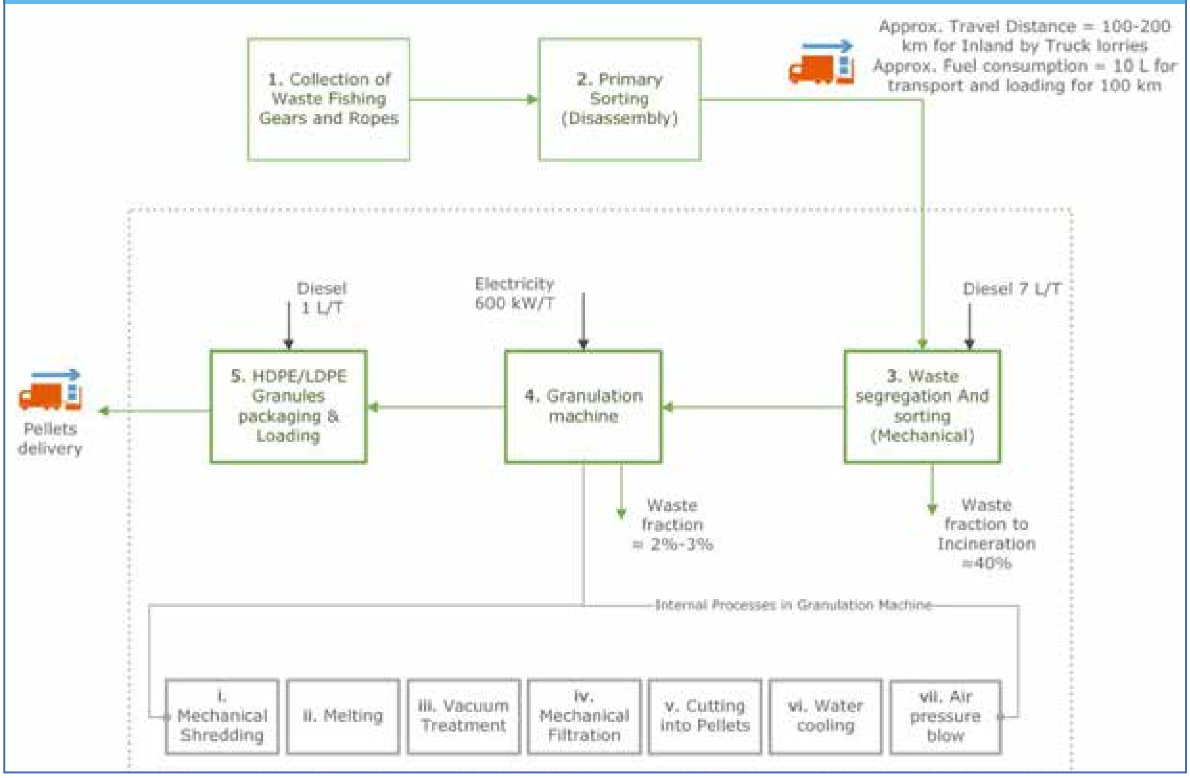
Smaller-sized, homogenous pieces of recyclable materials are obtained in the **cutting** or **shredding** stage; these make handling easier and enable material density separation. Unwanted fishing gear components that enter automated cutting and shredding machines must be clean of potentially harmful objects from the sorting stage. Indeed, cutting or shredding is essential to avoid damaging the machines during the recycling treatment, and to obtain a final product with a considerably reduced volume compared to that of the starting material. Waste shredding is a particularly complex process that involves a series of steps to shred the materials being recycled. Guillotine cutters are deemed more suitable than industrial shredders in some cases because they do not fluff up netting fibres from gillnets as much; this means that, compared to shredders, fewer residual sediments and contaminants become trapped.

A further **density separation** stage is necessary for unwanted fishing gears that are highly mixed and contaminated. This stage separates high-density materials (e.g. any remaining fragments of entangled gears, mussels and sediments) from lower-density polymer fibres for recycling and removes harmful contaminants that influence extrusion and recyclate material qualities. In contrast to the typically cleaner and pre-sorted EOLFG, ALDFG faces several more hurdles in the recycling pre-treatment process and the density separation stage is mostly required for these more contaminated and mixed ALDFG items (Stolte *et al.*, 2018). Twisted net lines and ropes, such as those from trawls, can often contain high levels of sediment that are also removed at this stage. A variety of other plastic separation techniques besides density separation that are available for plastics more broadly (i.e. not specific to unwanted fishing gear) are outlined by Serranti and Bonifazi (2019). Polymer identification technologies are additionally discussed in Section 1.2.3.

Following the cutting/shredding stage (and density separation stage, if required), polymer fibres from the unwanted fishing gears are **washed** to further remove impurities. This stage can be resource intensive: some experiments estimate that 100 kWh are required per tonne of fishing gear material being washed, and 1-3 m^3 of water (Schneider, 2020; Schneider *et al.*, 2023; Stolte *et al.*, 2018). Sometimes a further drying stage is required to remove any remaining humidity before proceeding to the polymer re-granulation phase.

After the washing process, the **grinding** process utilizes specialized machines equipped with rotating blades to cut the recyclable material into smaller fibres. The grinding process aims to improve the pourability of the resulting material for the re-granulation and injection moulding processes – if an extrusion of the material is desired. Grinding is not always necessary, however. For example, if clean nylon EOLFG material is cut into small nylon fragments without shredding, these materials are sufficiently pourable for immediate extrusion and the grinding process is not required. Stolte *et al.* (2018) quantified that the grinding machine employed in their ALDFG recycling experiments ground approximately 20 kg of washed material in 10 minutes.

FIGURE 5. TYPICAL PROCESS FLOW DIAGRAM FOR MECHANICAL RECYCLING OF EOL PLASTIC FG AND ROPES IN NORWAY



Source: Modified and adapted from Deshpande *et al.* (2020a). Multi-criteria decision analysis (MCDA) method for assessing the sustainability of end-of-life alternatives for waste plastics: A case study of Norway. Science of The Total Environment, 719, 137353. https://doi.org/10.1016/j.scitotenv.2020.137353.

An example of the mechanical recycling process is shown in Figure 5.

1.2.4.2 Tertiary recycling (chemical recycling, recovery and thermal conversion)

Chemical recovery, or chemical recycling (**tertiary recycling**) can be employed for those fractions of fishing gears that cannot be recycled mechanically under primary and secondary processes, or to produce a higher-quality end product if desired (e.g. depolymerization, see below). This process can act as an alternative to incineration or landfilling of unwanted fishing gears and components that are not possible to recycle using mechanical methods. Chemical recovery/recycling processes use chemicals and heat to break down plastic polymers into their constituent polymers or monomers and convert them into secondary raw materials. The word "chemical" is employed for these technologies since the polymer's chemical structure changes through these processes.

Chemical recycling processes employ a variety of technologies with an even wider variety of terminology that is sometimes used interchangeably, which can complicate and confuse discussions around this tertiary recycling approach (Manzuch *et al.*, 2021). Chemical recycling technologies are typically categorized as either **depolymerization** or **thermal conversion** processes. Because of the use of heat in depolymerization and thermal conversion processes, they are also sometimes referred to as thermochemical recycling. Dissolution/solvent-based purification is sometimes also included under tertiary recycling technologies as an advanced form of recycling, despite being a physical, not a chemical, process. While this report did not find applications for the latter with unwanted fishing gears, it is included given its relevance as a method for plastic waste recycling and given that it may have potential applications to recover plastic polymers in unwanted fishing gears in future.

Depolymerization involves breaking down polymers from pre-sorted, single polymer plastic waste into monomers that can be used as secondary raw materials in plastic production (CEFIC, 2023a). Because the monomers produced act as the building blocks for plastic production, the plastic products created from depolymerization are nearly identical in chemical and physical qualities to virgin plastics. However, this chemical recycling technology is limited to pre-sorted, single polymer fishing gears comprised of "polycondensates"[5] and not available for other gears comprised of mixed and/or "addition"[6] polymers (discussed in greater detail in Annex 1.1). At the time of this report, depolymerization is the only process that employs chemical recycling for the large-scale recycling of fishing gear and uses the secondary material stream for the production of new, high-quality fibres.

Thermal conversion uses thermal processes to convert mixed-plastic polymers into simpler molecules; these are usually liquids/oils (pyrolysis) or gases (gasification including steam reforming), with the potential to be used as feedstocks for petrochemical processes (Al-Salem *et al.*, 2009). Thermal conversion can also be employed for sorting and processing leftover materials and by-products from mechanical recycling processes to generate fuels, with technical feasibility dependent upon the polymer and by-product mix (Annex 1.2). Lead and other metal components from unwanted fishing gears can be separated using these thermal processes while preserving the energy value of the polymer molecules. The high market value of lead and other metals can incentivize the recycling of these materials rather than paying for hazardous waste disposal or landfill.

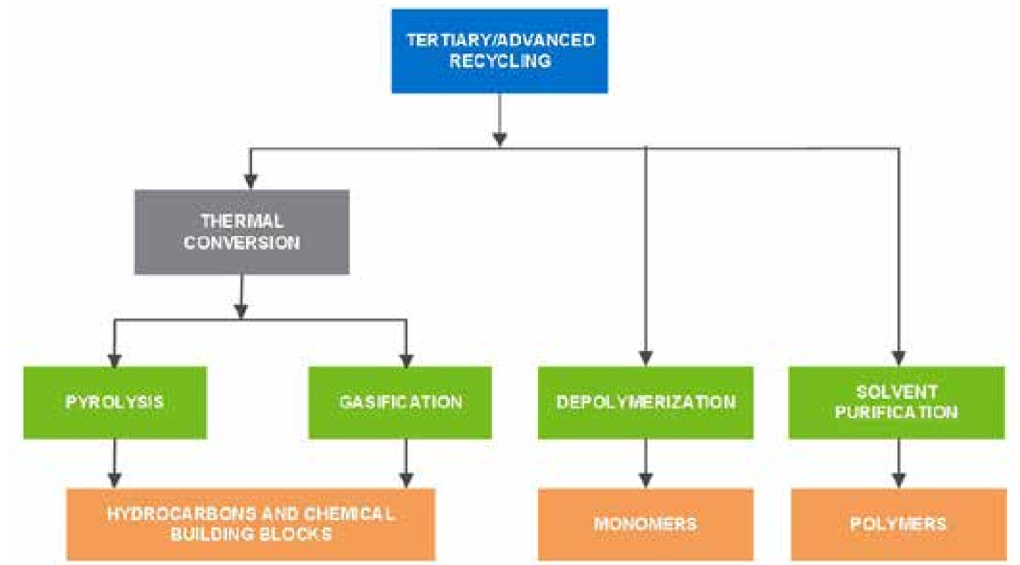
These thermal conversion technologies are criticized, however, as not constituting a circular economy approach (see Section 1.4 for more detail) given that the liquid and gaseous fuels produced represent lower overall quality or value products than the original fishing gear recycled. As such, some argue that these thermal conversion processes should be classified as quaternary processes under energy recovery and should not be included under the recycling definition. Others suggest that they should be broadly classified as "Other recovery" methods, with pyrolysis and gasification (Annex 1.2) and grouped with energy recovery processes. In Europe, for example, the definition of chemical recycling only includes the production of substances that can be used in the manufacturing of products (i.e. products or raw materials), and does not include fuel outputs. In other regions such as North America, chemical recycling does include fuel under the definition of "recycled" outputs (Chemical Recycling Europe, 2019).

The advanced recycling process of dissolution/solvent-based purification uses solvents to dissolve sorted plastic waste and separate plastic additives from recovered constituent polymers, which can be used in the production of new recycled plastic materials (CEFIC, 2023b; ICES, 2022). Dissolution/solvent-based purification is included in this report given its broad inclusion and frequent references in technical and grey literature, and around chemical recycling discussions, despite it being a physical, not a chemical, process, given that no chemical changes occur with the polymers recovered (Dolan, 2022; Hann and Connock, 2020; Manzuch *et al.*, 2021; The Consumer Goods Forum, 2022). As such, some have proposed that this type of recycling would be better categorized as a "physical recycling" process, which would include mechanical and dissolution processes as secondary recycling processes, with "chemical recycling" processes (i.e. depolymerization and, under some definitions, thermal conversion) categorized as tertiary recycling.

5 The polymerization process of monomers being joined together with a small molecule, such as water or methanol, lost as a by-product **Clark, J.** 2021 Condensation polymerisation. Chemguide: Core chemistry 14-16, available at https://www.chemguide.uk/14to16/organic/condpolymers.html. These include polyesters (PET), polyamides (PA, e.g. nylon), and polyurethanes (PU).

6 Double-bonded polymers formed by linking/chain reactions with other monomers, without the production of any by-products **Bishop**, 2013. Addition (Chain-Growth) Polymers. *An introduction to chemistry* by Mark Bishop. Chiral Publishing Company, available at https://preparatorychemistry.com/Bishop_Addition_Polymers.htm. These include polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC).

FIGURE 6. SUMMARY OF MAIN TERTIARY RECYCLING PROCESSES



Source: Dolan (2022). Solvent-based purification - A good fit between mechanical and chemical recycling. NexantECA, available at https://www.nexanteca.com/blog/202207/solvent-based-purification-%E2%80%93-good-fit-between-mechanical-and-chemical-recycling.

Dissolution/solvent-based purification technologies are still relatively new and largely in developmental and pilot stages, with target feedstocks including polyvinyl chloride (PVC), polystyrene (PS), polyethylene (PE) and polypropylene (PP) (Dolan, 2022; ICES, 2022). To the authors' knowledge and based on available research, at the time of this report dissolution had not been trialled for fishing gear recycling. It has been included by virtue of its applicability to plastic recycling and the chance that such applications might be trialled or extended to fishing gear in the future.

The tertiary/advanced recycling processes described above are summarized in Figure 6 and are outlined in additional detail in Annex 1.

The polymer composition of unwanted fishing gears, including the presence of mixed versus single polymers and together with the degree of contamination, will largely determine which tertiary technology is most appropriate for fishing gear recycling, along with any pre-processing requirements such as sorting, cleaning and cutting/shredding.

Tertiary/advanced recycling methods, including chemical recycling specifically, have the potential to result in high-quality outputs that are suitable for multiple recurring material circulations (e.g. the production of monomers from depolymerization that can be used as secondary materials for further plastic production). They also generally require less pre-processing work (primarily basic pre-sorting and cutting/shredding, depending upon the gear type and process) compared to mechanical recycling processes. However, chemical recycling technologies do often have high operational costs, substantial energy requirements, and require large volumes of waste inputs; with the exception of depolymerization, some are also still in developmental and pilot phases (European Commission, 2020a). The requirement for the application of further chemical or mineral additives to the recovered monomers and polymers from these processes, in order to achieve necessary performance qualities as secondary material feedstocks, has also been criticized. The high amounts of energy inputs required are a further concern, as are the hazardous toxic wastes and pollutants generated (particularly in thermal conversion processes), especially if not responsibly managed (NRDC, 2022; Ocean Conservancy, 2022).

1.2.4.3 Quaternary recycling (energy recovery)

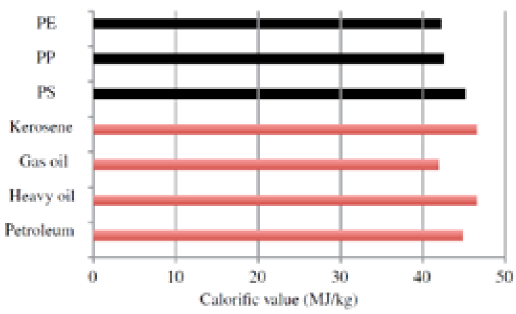
For waste fractions in unwanted fishing gears that are rich in plastics and not possible to recycle using primary, secondary or tertiary processes, quaternary technologies offer an alternative to convert these remaining materials into energy sources. **Energy recovery** implies burning (i.e. combusting, incinerating) waste to produce energy in the form of heat, steam and electricity (Al-Salem *et al.*, 2009). Energy recovery can reduce the amount of otherwise unrecyclable unwanted fishing gears and their components being sent to the landfill, while recovering valuable energy resources in the process.

As discussed in Section 1.2.4.2 for thermal conversion processes that generate fuel outputs, energy recovery is not always included under recycling definitions, because energy is produced in the form of heat, steam and electricity rather than substances which can be used in the manufacture of new products (i.e. products or raw materials). As such, some suggest that it should be more broadly categorized under "other recovery" methods, which would include pyrolysis and gasification (see Section 1.2.4.2 and Annex 1.2). It is included in this report given its broad inclusion in the recycling literature and the opportunity to recovery energy from fishing gears and components that are not recyclable under primary, secondary or tertiary processes.

The high embodied energy of plastic solid waste (PSW) and the thermal energy that can be extracted from it as a solid fuel are the main arguments for considering PSW as a resource. Figure 7 depicts the comparable heating values of plastics (in the form of polyethylene [PE], polypropylene [PP] and polystyrene [PS]) compared to traditional petroleum-based fuels (kerosene, gas oil, heavy oil and petroleum).

Burning PSW along with other municipal waste (often referred to as co-incineration) in sophisticated incinerators can provide heat and steam to drive turbine blades and produce power for local power grids. Co-incinerating unwanted fishing gears raises a variety of environmental concerns however, which chiefly concern the release of air pollutants such as CO_2, NOx, and SOx, and pollution arising from high chlorine concentrations in some fishing gear waste materials, such as polyvinyl chloride (PVC) (Frosch and Gallopoulos, 1989). In response to these pollution concerns, most modern incineration plants have sophisticated flue gas cleaning systems (Speight, 2019); (Bertling and Nühlen, 2019).

FIGURE 7. PLASTICS AND CONVENTIONAL FUELS COMPARED IN TERMS OF THEIR HEATING VALUES



Item	Calorific value (MJ kg^{-1})
Polyethylene	43.3–46.5
Polypropylene	46.50
Polystyrene	41.90
Kerosene	46.50
Gas oil	45.20
Heavy oil	42.50
Petroleum	42.3
Household PSW mixture	31.8

Source: Modified and adapted from Andrady (2015). Plastics and environmental sustainability. John Wiley & Sons, Inc (https://onlinelibrary.wiley.com/doi/book/10.1002/9781119009405) and Al-Salem *et al.* (2009). Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Management, 29(10), 2625-2643 (https://doi.org/10.1016/j.wasman.2009.06.004).

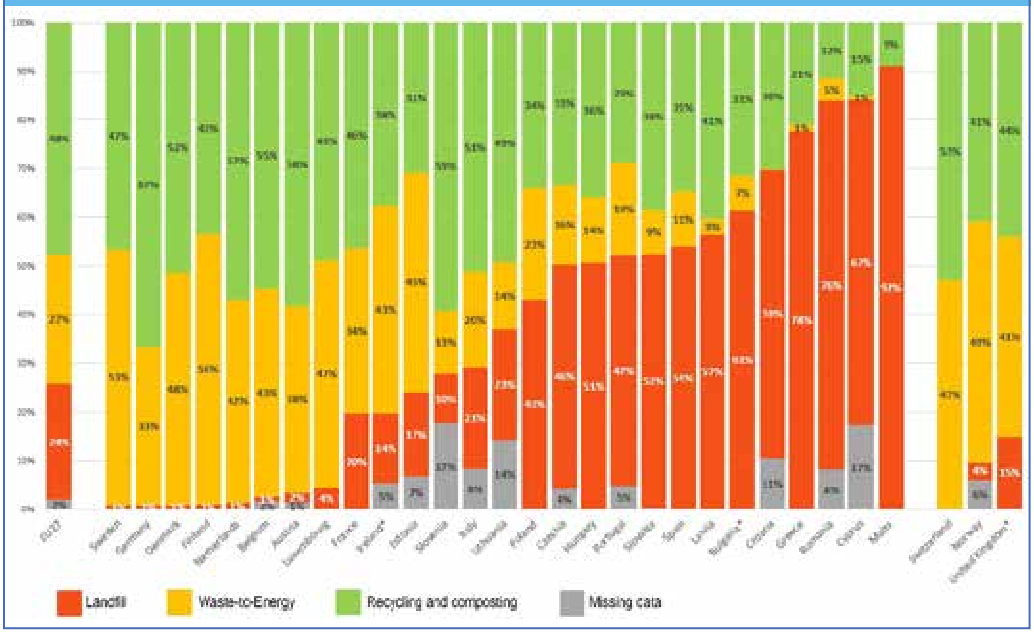
[7] Slag is formed in the course of burning garbage and contains heavy metals including aluminium, copper, zinc and lead. Slag from incineration plants needs to be directed for additional processing to recover valuable waste components and decrease negative environmental impacts from this material at the storage stage (Kolodezhnaya *et al.*, 2019).

In addition to the release of air pollutants from incineration outlined above, incineration primarily creates mineral wastes (e.g. ash and slag),[7] which contain oxidized particles, and organic and inorganic contaminants (Bertling and Nühlen, 2019; Stolte *et al.*, 2018)2018. By virtue of their lightweight characteristics, the ash can leave the incineration facility via the flue gas path. Because ashes can be highly toxic, they are regularly collected and transported to secure disposal sites such as landfills and mines for safe, end-of-life storage (Bertling and Nühlen, 2019). Al-Salem *et al.* (2009) and Yassin *et al.* (2005) provide extensive information regarding thermal processing systems for energy recovery from solid wastes, and the collection and removal of flue gases.

In many countries and regions, such in Japan and across Europe, waste-to-energy technologies are managed in accordance with established standards under well-developed regulatory frameworks. Figure 8 provides an example of the regional prevalence of waste incineration in Europe. While waste-to-energy/energy recovery is typically categorized as quaternary recycling, in the case of Figure 8, it has been defined separately from recycling methods given the non-circular nature of this end-of-life waste treatment.

Without adequate financial investment, education, and capacity building, there is a risk that the use of incinerators to generate energy can result in severe adverse health and environmental impacts (see pollution by-products outlined above). Concerns around quaternary recycling processes include: high costs for facilities, including to build, maintain, and to meet modern emission standards; long distances and associated financial and fossil fuel requirements to transport the materials; a lack of transparency and oversight in some countries to ensure that pollution prevention standards are met; and diminished support for alternative strategies to minimize single-use plastic production, use and subsequent waste creation and to promote the Redesign-Reduce-Reuse-Recycle philosophy (UNEP, 2016). Given these concerns, quaternary recycling processes are only considered to be a sensible method for waste treatment when primary to tertiary recycling processes fail due to economic or technological constraints.

FIGURE 8. MUNICIPAL WASTE TREATMENT IN EACH EU27 MEMBER STATE (PLUS NORWAY, SWITZERLAND AND THE UNITED KINGDOM), SORTED BY SHARE OF LANDFILL IN 2019



Source: Adapted from CEWEP (2021). Latest Eurostat Figures: Municipal Waste Treatment 2019 (Eurostat data March 2021), Confederation of European Waste-to-Energy Plants (CEWEP), available at https://www.cewep.eu/municipal-waste-treatment-2019

1.2.5 Opportunities and challenges presented by fishing gear recycling methods

The choice of the fishing gear recycling method will be determined by the type of plastic polymers present in the gears and gear components, the material purity (grade), degree of contamination, the availability and maturity of recycling technologies, and their viability in different socioeconomic environments (Singh *et al.*, 2017). For example, Schwarz *et al.* (2021) demonstrate that the optimal plastic recycling technology varies according to the material's polymer composition and that multiple and complementary technologies can be applied across different plastic waste streams. Schwarz *et al.* (2021) underline that optimal environmental performance can only be obtained in recycling where pre-treatment is improved. If the plastic materials in EOLFG or recovered ALDFG are of poor quality as a result of high degrees of contamination or impure polymers, one can expect the gear to undergo prolonged treatment, which will require several technical treatment procedures.

The type of unwanted fishing gear being recycled will also influence the recycling method employed, including associated pre-processing requirements. For example, ALDFG gillnets can be challenging to recycle using mechanical processes as the fibre materials generated typically contain a polymer mix that can include polyamide (PA), polyethylene terephthalate (PET), polypropylene (PP) and polyethylene (PE), as well as a variety of contaminants (e.g. lead, salt) and organic pollutants that are often not possible to remove entirely during pre-processing procedures. Procedures exist to deal with a variety of sometimes complicated to recycle fishing gears, but these will vary depending upon several factors, namely: the specific gear type, gear components (e.g. float and sink lines, lead and other metals); the degree of contamination; and the specific polymer mix (or single polymer composition such as pure PE trawl netting or pure PET ropes). Certain gear materials will not be recyclable with some technologies, but possible with others. *Dyneema*, for example, is generally not suitable for mechanical recycling processes, since the material does not melt but rather burns; as a result it is considered best suited for tertiary recycling processes.

Mechanical recycling (primary and secondary recycling) for fishing gears requires a more involved pre-treatment process than any of the thermal conversion (tertiary recycling) or energy recovery (quaternary recycling) routes. In mechanical recycling, plastics in fishing gears need to be sorted, with the removal of any coarse pollutants, followed by shredding, density separation (most often for more contaminated ALDFG), washing and grinding (Figure 4). Depolymerization processes (tertiary recycling, see below) also require clean, uncontaminated, pre-sorted single polymer inputs. By comparison, thermal conversion processes require more basic pre-sorting and shredding, with minimal to no pre-processing requirements for the incineration of unwanted fishing gears in energy recovery processes.

Stakeholder involvement, capacity building and supporting technological developments and innovation[8] can make mechanical recycling (and depolymerization processes) more efficient when compared to the other typically more expensive and energy-intensive tertiary and quaternary recycling options. Involving fishing gear producers, vendors and fishers in the collection and sorting stages can improve the quality of the sorted fishing gear fractions for recycling, given their knowledge and expertise on the properties of the materials. Innovations can include technologies that improve upon current plastic polymer identification methods, and any substances of concern contained in different fishing gears. They may also involve better automated sorting mechanisms that differentiate between plastic types and colours.

[8] Such as improved systems for the collection, sorting (including polymer identification) and reprocessing of recyclable plastics.

The redesign of plastic products that integrate recyclability considerations into materials at the design and manufacturing stages (e.g. single polymer versus multi-polymer products), can further enhance the efficiency of mechanical recycling at the end of a products' life. Strong secondary markets for recycled materials are also essential to supporting and boosting recycling rates: with the recycling process driven by the specific market demand, they facilitate mechanical and chemical recycling processes. These secondary markets can be supported by regulatory measures that encourage the demand for recycled products, such as the requirement to include minimum percentages of recycled plastic in new products.

Tertiary recycling processes (chemical recycling, recovery and thermal conversion) can act as complementary alternatives to mechanical recycling for unwanted fishing gears and their components that are too difficult to recycle under primary and secondary recycling processes, particularly ALDFG. Depolymerization processes can also be employed for some fishing gear materials that are possible to recycle under mechanical processes because of the potential to generate virgin polymers from the input materials that can be used to produce higher-value products (e.g. yarns used in clothing products). The plastics produced from depolymerization processes are valued for their physical and chemical properties that perform like virgin materials; however, they are also sometimes criticized for the requirement of new additives and chemicals to produce these plastics. At the time of this report, depolymerization is the only process that employs chemical processes for the large-scale recycling of fishing gear and uses the secondary material stream for the production of new, high-quality fibres.

Compared to quaternary recycling processes, tertiary recycling also offers a broader range of outputs, including the recovery of constituent plastic monomers (depolymerization) and polymers (dissolution/solvent-based purification, depolymerization for shorter fragments of polymers). These can be used as raw materials in the production of new plastic materials, as well as flexible energy returns in the form of liquid oil fuels or synthetic gases (thermal conversion). Thermal conversion processes can generally accept more mixed, contaminated and lower grade polymers (e.g. contaminated and mixed recovered ALDFG) compared to mechanical recycling. Thermal conversion procedures additionally maintain the benefit of extracting lead and other metal components from gears such as footropes in trawls and lead lines in gillnets and trammel nets (Bertling and Nühlen, 2019).[9]

A number of criticisms also exist in relation to tertiary recycling processes. They include: a lack of data and transparency around the technical processes; a lack of data and transparency around commercial and financial viability; scalability; the ability of these technologies to take highly contaminated and mixed polymer feedstocks; and post-processing requirements including decontamination and pollution controls.

Many concerns also relate to the environmental and human health impacts from thermal conversion processes, from the resulting hazardous wastes and emissions (NRDC, 2022; Ocean Conservancy, 2022). Primary concerns in this regard include the generation of large amounts of hazardous waste, the storage or release of hazardous chemicals on site, thermal conversion plants largely sited in low-income communities, difficulty with scalability, the production of contaminated end products and a large carbon footprint (NRDC, 2022). Manzuch *et al.* (2021) provide a relatively comprehensive literature review on chemical recycling technologies; it includes more detailed information on pollutants, including substances of concern and pollution controls/best available techniques and regulatory considerations to address these issues.

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9 Noting that the "acceptable guidance value" for lead content must not exceed 3.3 g of lead produced by these procedures per kg of fuel (Bertling and Nühlen, 2019).

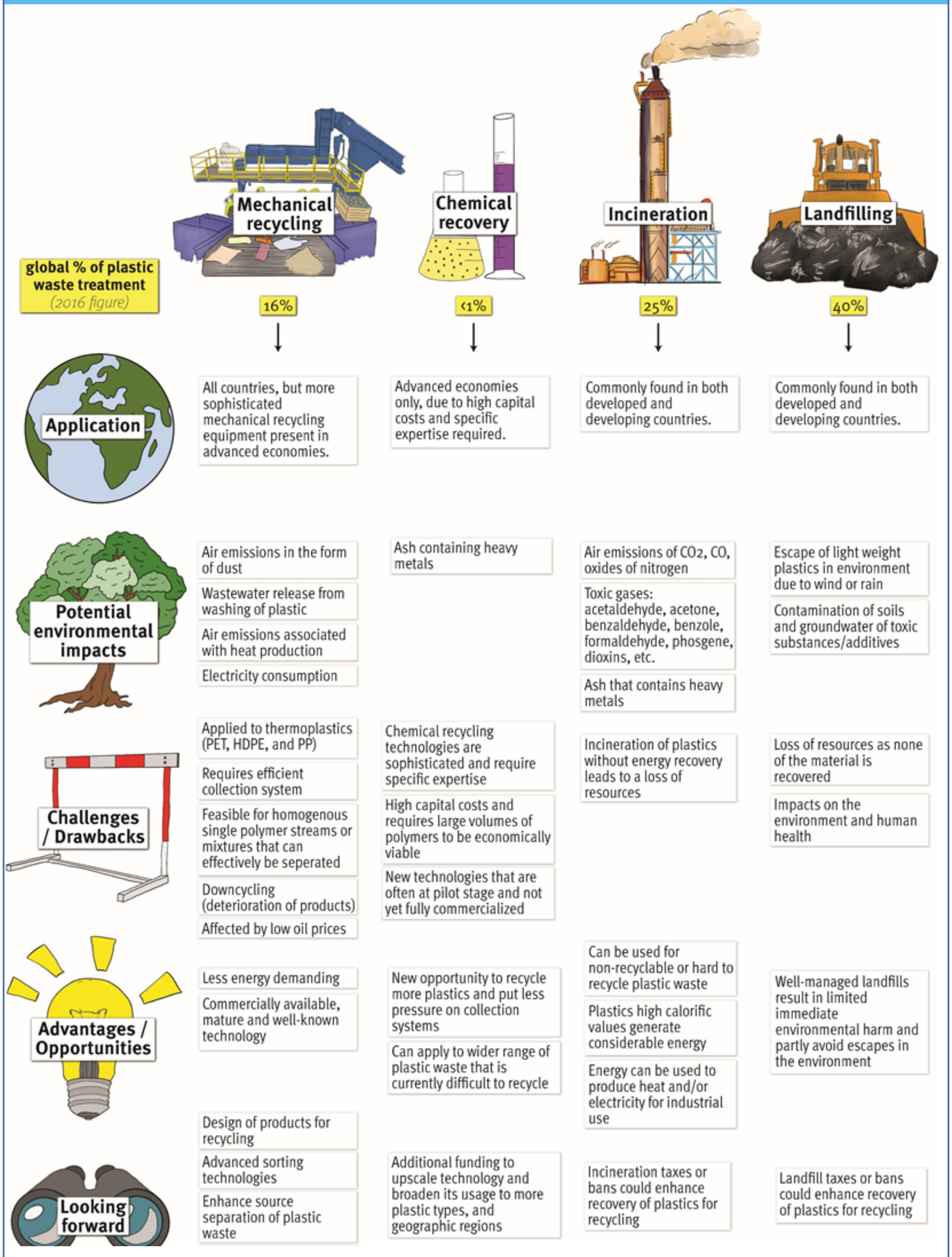
There are also concerns with regard to defining thermal conversion technologies as recycling processes, given that many existing thermal conversion technologies are used to create fuel rather than converting these materials into monomers and polymers that can be reintroduced to the plastic production process. As noted in Section 1.2.4.2 on tertiary recycling processes, the European Union does not include fuel outputs from chemical recovery processes under their definition of tertiary recycling methods (Chemical Recycling Europe, 2019). Many thermal conversion plants are also often experimental facilities with processes often only undertaken as pilot studies (Bertling and Nühlen, 2019; Stolte *et al.*, 2019)2019.

Greater transparency and more information is required to prove the larger-scale commercial viability of some tertiary recycling technologies for unwanted fishing gears, particularly thermal conversion and dissolution/solvent-based purification processes. Further research is required to continue to improve tertiary recycling methods to better accommodate more mixed plastic waste, including traditionally non-recyclable polymers (in the case of thermal conversion processes). More development is needed on the repeated recycling of recovered polymers (particularly for depolymerization and dissolution/solvent-based purification), and to replicate and scale up proven technologies (e.g. depolymerization technologies for unwanted fishing gears) (Solis and Silveira, 2020; Zhu *et al.*, 2018). Annex 1.4 further discusses the advantages and disadvantages from the main chemical recycling technologies summarized in this report.

When primary, secondary and tertiary recycling technologies are not available for unwanted fishing gears, **quaternary recycling processes** can serve as an alternative option to landfill through **energy recovery** from incineration. These expensive energy recovery systems must be outfitted with appropriate flue gas cleaning systems to filter hazardous air emissions and to responsibly handle and manage ashes produced from the incineration processes. As energy recovery technologies generally do not remove the need for waste minimization and require relatively large amounts of consistent waste inputs for energy generation, some argue that they can ultimately work against the waste minimization principles that recycling, reuse, and reduction approaches strive to support.

While incineration technologies are widely available globally (Figure 9), more advanced energy recovery systems are less common due to the high costs for the infrastructure and technologies. Indeed, they require large volumes of waste inputs and stringent pollution controls, including post-incineration cleaning systems, to remove residual contaminants and toxins. Despite its rapid development, chemical recycling is also not a common recycling procedure globally given the overall high resource requirements (capital, expertise and energy). This creates limitations for its use and uptake, especially in developing parts of the world and for smaller population centres in more remote locations (Figure 9). By contrast, mechanical recycling is more common globally given that it is less expensive to implement, less energy-intensive, and more accessible for small-scale recycling operations – including in developing and remote parts of the world, and for smaller population centres (Figure 9). To establish globally responsible waste management systems for fishing gear and other plastic waste streams, improving technological capacity in lower-income countries, especially those depending heavily on the fishing sector, will be essential.

FIGURE 9. RECYCLING, RECOVERY, AND FINAL DISPOSAL OF PLASTIC WASTE



Source: Illustration modified and adapted from UNEP (2021). Drowning in Plastics - Marine Litter and Plastic Waste Vital Graphics. United Nations Environment Programme (UNEP), Job No DEP/2386/NA (https://www.unep.org/resources/report/drowning-plastics-marine-litter-and-plastic-waste-vital-graphics).

Figure 9 summarizes some of main advantages and disadvantages of different recycling techniques (and landfill) options.

The following additional considerations are employed in life-cycle assessments (LCA) for different recycling options: 1) the energy use required for different processes, including from pre-processing, transport and post-processing requirements;

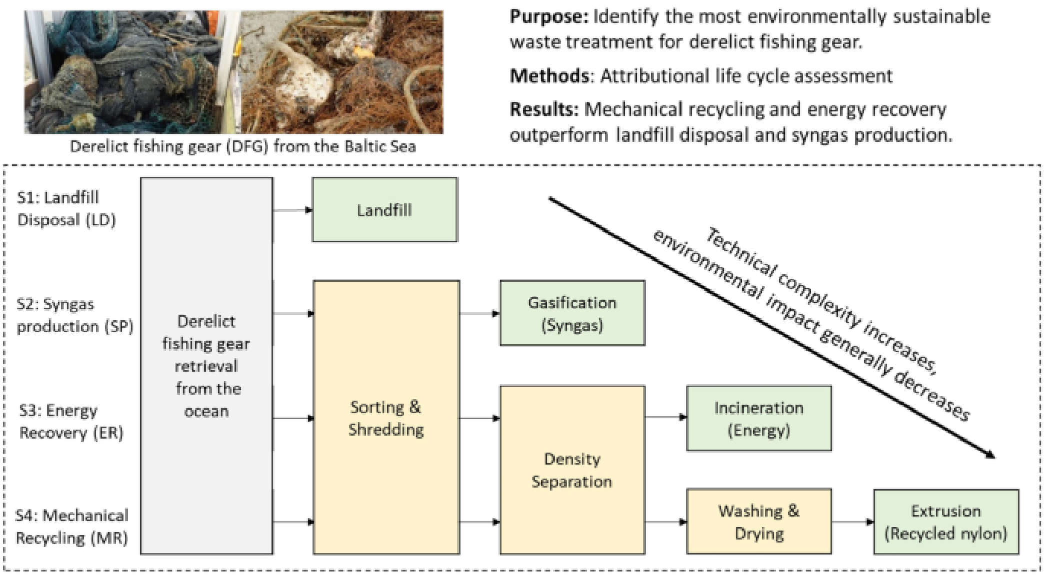
2) the quality of input and output material streams, including the yield of the desired products from these outputs; 3) the environmental burdens, including production of pollutants; and 4) material traceability and social and economic impact assessments (Hann and Connock, 2020; Schneider *et al.*, 2023). Techno-economic assessments can also be undertaken for different recycling processes for unwanted fishing gears to provide stronger better quantitative considerations of what might be available for different gears and their associated waste streams; e.g. see Table 5-6 in Manzuch *et al.* (2021).

The first LCA undertaken to compare environmental impacts from different waste treatment scenarios of ALDFG in Europe concluded that mechanical recycling, followed by energy recovery, had the lowest overall environmental impacts (Schneider *et al.*, 2023). On the other hand, gasification to produce syngas (i.e. synthetic gas, in a thermal conversion process, see Annex 1.2) and landfill had higher overall environmental impacts (Figure 10). The four waste treatment scenarios examined are listed from S1 to S4, in Figure 10.

The high environmental impacts from the syngas production results from the high electricity requirements for this waste treatment option. Overall, the study found that across treatment schemes the greatest impacts arose from ALDFG retrieval, metal recycling, and waste treatment processes, while environmental impacts from fishing gear transport and pre-treatment contributed less, by comparison (Schneider *et al.*, 2023).

The first sustainability assessment of typical end-of-life treatment options for recovered ALDFG and EOLFG in Norway used multicriteria decision-making, together with LCA screening, to conclude that the location of mechanical recycling facilities is a key factor to consider in fishing gear recycling (Deshpande *et al.*, 2020a); see Section 1.3.4 for a discussion around centralized and decentralized waste management infrastructure. The consideration of recycling location, "recycling (inland)" – i.e. non-exported recycling/recycling within Norway – was the preferred end-of-life treatment option, followed by incineration, landfill and recycling for export, outside of Norway (Deshpande *et al.*, 2020a).

FIGURE 10. LIFE-CYCLE ASSESSMENT (LCA) ON WASTE MANAGEMENT OPTIONS FOR DERELICT FISHING GEAR



Source: Adapted from Schneider *et al.* (2023). Life cycle assessment (LCA) on waste management options for derelict fishing gear. The International Journal of Life Cycle Assessment, 28(3), 274-290 (10.1007/s11367-022-02132-y).

However, other studies have found a range of differing results with respect to environmental impacts, following the comparison of different recycling technologies, and depending on the specific technologies investigated; see for example Table 5-5 in Manzuch *et al.* (2021). As a result, Schneider *et al.* (2023) noted the importance of undertaking case-specific LCAs for different waste treatments and technologies being considered (Schneider *et al.*, 2023). Other assessment tools such as material flow analyses[10] (Deshpande *et al.*, 2020b) can also inform LCAs, as can a consideration of the opportunities and challenges presented by different fishing gear recycling technologies for case-specific contexts, and at locally and regionally relevant scales.

1.3 TECHNICAL MEASURES AND POLICY/REGULATORY INSTRUMENTS TO SUPPORT FISHING GEAR RECYCLING

This section summarizes a variety of technical measures, policy and regulatory instruments that can support fishing gear recycling. These measures and instruments can be supported at local, regional and global scales by management, policy and legislative measures, as well as by the public and private sectors. They support responsible unwanted fishing gear management efforts including the waste management of EOLFG and recovered ALDFG and can also act as ALDFG preventative measures.

1.3.1 Design for recyclability

Designing fishing gears for recyclability at the end of their life is a technical measure that can improve opportunities for – and the quality of – fishing gear recycling. Fishing gears are often created from a variety of polymers and are highly customized to fulfil the functional criteria of each gear (see Section 1.2.1 on Fishing gear design and manufacturing). Highly specialized fishing gear designs with multiple polymers and additives can make recycling more difficult, more expensive, and can result in lower-quality recycled plastic items produced.

Section 1.4 discusses fishing gear design strategies to improve product circularity in great detail. Key design strategies to increase the recyclability of fishing gears specifically, include: minimizing the number of mixed polymers, and ideally using clearly labelled single polymers that can be easily identified at the end of their life. Fishing gear designers and manufacturers can also aim to exclude, wherever possible, non-recyclable materials, and materials and components prone to regular loss in the marine environment. Elsewhere, they can reduce the use of dark pigments which are typically more difficult to recycle, and reduce the use of certain polymers and other hazardous materials that present barriers or inhibit the ability to recycle gears at the end of their life, or which present environmental and health concerns during the recycling process (European Commission, 2020b; UNEP, 2016). Furthermore, gears can be designed, manufactured and assembled with the aim to make the eventual disassembly process simpler, including by simplifying some of the gear components. A 2020 study produced by the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) provides more information on regional best practice considerations for the design and recyclability of fishing gear (OSPAR Commission, 2020).

Gear and polymer identification technologies can also assist in designing gears for recyclability. Gear identification technologies can include a wide variety of gear marking technologies (see Section 1.3.2 on fishing gear marking). Possibilities include the digital watermarking of fishing gears and their component plastic parts at the design

[10] Material flow analyses follow the basic principle of conservation of matter and energy in isolated systems and the mass-balance principle and can be used as decision-support tools for resource management (Deshpande *et al.*, 2020b).

stage,[11] which contains information around the polymer composition to facilitate recycling pre-treatment, notably the material sorting and density separation stages. Information could also be included regarding recommended lifespans for fishing gears (i.e. "use-by" dates), with information such as the date of manufacture and anticipated useful lifetime. This information would help fishers and regulators ensure that gears are efficiently repaired, replaced and responsibly disposed of, and not used beyond their safe working life. Technologies exist that can scan plastic materials and identify the type(s) of plastic polymer(s) that a material is composed of, such as PE or PA (see discussion in Section 1.2.3 on technologies that improve current identification methods of different plastic polymers).

National and regional policies and regulatory frameworks can also support and accelerate improved fishing gear designs for recyclability. For example, requirements concerning the inclusion of recyclable materials in fishing gears at the design and manufacturing stages have been discussed in the European regional context (European Commission, 2020a). If the incorporation of recycled materials into fishing gears themselves is desired, then the strength and strain of recycled waste materials,[12] as well as their cost, should be comparable with virgin materials, in order to facilitate uptake by the fishing industry. Increased research and innovation are needed to enhance the development and manufacture of recyclable materials for application in the marine environment with the physical and mechanical properties of virgin materials (e.g. breaking strength, flexibility, resistance to abrasion and strain), as well as a comparable resilience to better ensure uptake by the fishing industry.

1.3.2 Fishing gear marking

Marking fishing gears is an important tool to support better gear stewardship through its use and end of life, to discourage fishers from discarding gears at sea, and to reduce ALDFG (FAO, 2019b, 2019c, 2022; OSPAR Commission, 2020). By creating a link between the ALDFG recovered and the fisher or vessel responsible, gear that was accidentally lost can be returned to the owner for reuse, **recycling** or other safe disposal (Brodbeck, 2016; FAO, 2015). Marked gears also support fisheries authorities to enforce penalties for intentionally dumping fishing gear in the marine environment. However, if gear marking requirements are especially onerous or result in penalties for what is otherwise considered normal gear loss resulting from normal operations, fishers may be dissuaded from wanting to mark their gear at all.

Macfadyen *et al.* (2009) recommend that gear marking technology be an intrinsic feature of the gear that can be incorporated during manufacture and assembly operations. Gear marking to identify the producer(s)/manufacturer(s) at the production/assembly stage facilitates fishing gear Extended Producer Responsibility (EPR) schemes (see Section 1.3.6 on EPR for fishing gears) and gear traceability efforts. Improved gear traceability, tracking and recovery allows for responsible gear stewardship throughout the gear's use and the end of its life. The latter includes supporting unwanted fishing gear collection and return systems from which gears can be recycled (OSPAR Commission, 2020). Gear marking can also support efforts to prevent, identify and enforce regulations against illegal fishing activities, which are a driver of ALDFG in some areas of the world (e.g. fishers operating illegally will sometimes discard their gears after use, or abandon them prior to vessel inspections) (Richardson *et al.*, 2018).

[11] Digital watermarking is the process of embedding a digital code/watermark/data into digital multimedia content – e.g. images, audio or video.

[12] Strain is the ratio of the change in length to the original length, sometimes expressed as a percent. Tensile tests use plots of stress vs strain to display results **Sala, A., Lucchetti, A. & Buglioni, G.** 2004. The change in physical properties of some nylon (PA) netting samples before and after use. *Fisheries Research*, 69(2), 181-188. https://doi.org/10.1016/j.fishres.2004.05.005. Strain is an important parameter for fishing gears, because the mesh width in fishing nets is legally restricted to certain sizes in many net fisheries, which are not allowed to change during use in the marine environment.

TABLE 2. TYPES OF INFORMATION THAT CAN BE INCLUDED ON FISHING GEAR MARKS

Information	Description
Country code	• Three alphabetic letters (ISO3) detailing the flag state of the vessel – i.e. the state under whose laws the fishing vessel is registered.
Ownership identifiers – unique vessel identifiers (UVI)	• Global identifiers: IMO number (where available), international radio call sign (IRCS) and Maritime Mobile Service Identity (MMSI) number. • Regional identifiers: Where relevant, the name of a regional fisheries management organization (RFMO) with which the vessel is registered and authorized to operate (e.g. IOTC) and if applicable the RFMO registration assigned to the vessel. • National identifiers such as the registration or vessel licence number. Additionally/alternatively it may be appropriate to use the company name, fishing licence/permit number, fisher name or contact details of the operator (especially for gears not operated from a vessel).
Date	• Monitoring the age of the fishing gear or its first year of use. • Indicating its legal use for a particular year.
Gear code	• Gear code: If found after being lost, this provides information on the type of fishing gear, even if only part of the gear is found. • The gear code also provides assurance that markers issued for the gear type are attached to the correct type of gear. • Unique Gear Sequential number, for fishers to check if using many units of gear, or alternatively where licensing requires units of gear to be sequentially numbered.
Contact details	• Contact information (email, website or phone number) for a representative of the vessel owner or operator.

Source: Modified and adapted from Einarsson *et al.* (2023). Voluntary Guidelines on the Marking of Fishing Gear – Manual for the marking of fishing gear. Suppl. 2. FAO, Rome, Italy. Available at https://doi.org/10.4060/cc4251en

Marking establishes clear ownership of the gears and assists with the monitoring and management efforts of these gears within their associated fisheries (FAO, 2019a).

A variety of methods can be used to mark fishing gear, for a variety of purposes. Gears can be marked: to **identify ownership, including by a fisher and/or vessel; to confirm legality of a fishing gear; and to indicate a fishing gear's position in the water.** Gear marking can also include **identification of the material and polymer composition of fishing gears.** This facilitates gear dismantling at the end of its life, to separate recyclable from unrecyclable materials, sorting and density separation recycling pre-processing requirements, as well as the decision around the best available recycling option for the polymers which make up the unwanted gears.

FAO's Manual for the Marking of Fishing Gear details fishing gear marking methods specifically intended to **identify ownership and confirm legality of the fishing gear** (Einarsson *et al.*, 2023). Gears are often marked for identification purposes with the fishery license or registration number, "vessel identification" an International Maritime Organization (IMO) number or other forms of individual identification (Table 2) (Langedal *et al.*, 2020).

1.3.2.1 Voluntary Guidelines on the Marking of Fishing Gear (VGMFG)

The Food and Agriculture Organization of the United Nations (FAO)'s Voluntary Guidelines on the Marking of Fishing Gear (VGMFG) is the main international instrument available to address ALDFG at the global level. The VGMFG provide **guidance around the identification of ownership and position of fishing gear, and the legality of gear use, through provisions relating to gear marking systems, which include the retrieval and reporting of lost gear, and the responsible disposal of end-of-life gear** (Clarke *et al.*, 2014; FAO, 2018a). It outlines measures that prevent ALDFG and ghost fishing, facilitate the identification and recovery of ALDFG, and combat illegal, unreported and unregulated (IUU) fishing. The VGMFG complement FAO's **Code of Conduct for Responsible Fisheries** (see Section 1.3.7 on international policy instruments related to unwanted fishing gear). The guidelines also include a framework for undertaking risk assessments to identify the appropriateness of implementing a system for marking fishing gear, which was further developed by He and Lansley (2023). The guidelines are designed to be simple, pragmatic, affordable and verifiable; compatible with related fisheries traceability and certification systems; and recognize the special requirements of developing states and small-scale fisheries. Moreover, they outline opportunities to support fishing gear monitoring, control and surveillance (MCS), research and development, and awareness-raising, communication and capacity-building efforts.

As the VGMFG are voluntary in scope they are not directly enforceable; each country therefore determines the extent to which it implements the recommendations of the guidelines.[13] In this way, these voluntary measures benefit from being generally easier and faster to establish as they do not put binding commitments on countries, which means they can be wide-ranging in scope and include ambitious targets.

Although not the focus of the VGMFG, the guidelines support fishing gear recycling measures by providing recommendations for the reporting and recovery of ALDFG, and the sound disposal of unwanted fishing gears. Sections 43–45 specifically refer to support for fishing gear recycling:[14]

> 43. The relevant authority should encourage owners of the fishing gear to have adequate equipment and training available to facilitate the recovery of ALDFG. Where possible, the owner/operator and the relevant authority should collaborate to enhance recovery efforts. **Owners (national or foreign) should be informed of gear recovered (where appropriately marked) so that they can facilitate the collection of the recovered gear for <u>recycling</u>, re-use or safe disposal.**
>
> 44. **Recovered ALDFG and fishing gear no longer in use should be <u>recycled</u>**, or disposed of responsibly on land. States should ensure the provision of adequate port reception facilities for the disposal of such fishing gear in accordance with MARPOL Annex V.
>
> 45. **States and other interested parties are encouraged to support the development of infrastructure to enable the <u>recycling</u> of recovered ALDFG and fishing gear no longer in use** (FAO, 2019a).

1.3.3 Port reception facilities

Port reception facilities (PRFs) are dedicated facilities at ports designed to receive waste(s) from ships visiting the ports. They are extensively supported as part of the International Convention for the Prevention of Pollution from Ships (MARPOL), with Annex V specifically outlining the need for the provision of adequate garbage facilities in ports (IMO, 2016). In the case of unwanted fishing gears, PRFs serve as important infrastructure to allow for the dedicated collection of EOLFG and recovered ALDFG which can subsequently be prepared for recycling. Paragraph 44 of the VGMFG states that:

> Recovered ALDFG and fishing gear no longer in use should be **recycled** or disposed of responsibly on land. **States should ensure the provision of adequate port reception facilities for the disposal of such fishing gear** in accordance with MARPOL Annex V (FAO, 2019a; emphasis added).

[13] In contrast to the voluntary approach provided by the VGMFG, the Marine Environment Protection Committee of the International Maritime Organization (IMO) agreed in 2022 that a goal-based requirement for the mandatory marking of fishing gear should be developed under the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex V, which provides regulations for the prevention of pollution by garbage from ships, and instructed the Sub-Committee on Pollution Prevention and Response to develop draft amendments to MARPOL Annex V and associated guidelines accordingly (IMO, 2022). This work is ongoing and will require proposals and input by Parties to MARPOL Annex V and close cooperation with FAO in order to progress.

[14] Bolded and underlined sections added by the authors to clarify where recycling arises in the VGMFG.

FIGURE 11. FREE PORT RECEPTION FACILITIES FOR UNWANTED FISHING GEAR AND OTHER PLASTIC WASTE IN THE UNITED KINGDOM PROVIDED BY ODYSSEY INNOVATION'S NET REGENERATION SCHEME AND THE INDIGO PROJECT IN THE UNITED KINGDOM

Source: Adapted from Odyssey Innovation (2023a). Free port reception facilities for unwanted fishing gear and other plastic waste in the United Kingdom. Available at https://www.odysseyinnovation.com

Port reception facilities should be tailored to the requirements of each port. In small ports, for example, a container at the nearest fish reception facility or a regularly scheduled and announced collection of fishing gear might be a viable solution (Langedal *et al.*, 2020).

Larger ports with high volumes of fishing vessel traffic should generally plan for year-round collection of fishing gear and include basic facilities such as dedicated waste receptacles for EOLFG and recovered ALDFG. Depending on the location of waste bins and the amounts and types of wastes received, it may be necessary to sort and establish distinct material streams, including dedicated bins for unwanted fishing gears (UNEP, 2016). Maintaining specific colour schemes that are consistent for different material streams for bins and other receptacles, in addition to using clear images and text, helps users to make a quick decision about where to discard their waste materials. Figure 11 shows an example of dedicated reception facilities for end-of-life fishing gear in the United Kingdom.

It is also important to ensure the provision of effective communication tools and education initiatives so that fishers can utilize the PRFs effectively, including clear disposal procedures for unwanted gears. Prędki *et al.* (2019) indicate that there are sometimes shortcomings in the provision of information for harbour users, and fishers are not always aware of where, when or how unwanted fishing gear must or can be responsibly disposed of and collected. For example, in approximately half of Europe's fishing ports, unwanted fishing gears are usually disposed of in the same containers as other municipal waste (Prędki *et al.*, 2019). In many cases, the harbour personnel are unaware of what happens to the fishing gears that have been gathered separately, or if the waste management companies to whom the EOLFG and recovered ALDFG is transferred have the expertise and technological facilities needed to reprocess and recover the materials. Better awareness-raising and communication is required among and between fishers, port and harbour managers, and the waste management companies employed to handle the wastes received from PRFs, to facilitate the collection, segregation and responsible disposal and recycling of unwanted fishing gears.

The decision around waste management options for wastes collected by PRFs are dependent upon the volumes of unwanted fishing gears collected, the expenses and revenue associated with them, and the waste infrastructure that is locally accessible (Van Meel, 2022). A variety of market-based instruments and incentives may be provided to support the dedicated PRF collection of unwanted fishing gears, and to support the required recycling infrastructure for these gears. Market-based instruments that can support fishing gear recycling, including through the provision of PRFs, are discussed in Section 1.3.5.

National and regional policies and regulatory mechanisms can also support the collection of unwanted fishing gears in dedicated PRFs. For example, in Europe the revised Port Reception Facilities Directive (PRFD) (Communication COM (2018) 33, 2018) governs waste releases from all ships at sea, including fishing vessels and recreational vessels. It mandates that European Union Member States establish suitable port reception facilities and that ships transport their garbage to these facilities prior to leaving port. It also requires that port reception facilities include separate collection points for fishing gear and "passively fished waste" (i.e. waste collected from gears during fishing operations). The PRFD additionally includes indirect costs for waste transportation to ports,[15] including for unwanted fishing gears and operational waste.

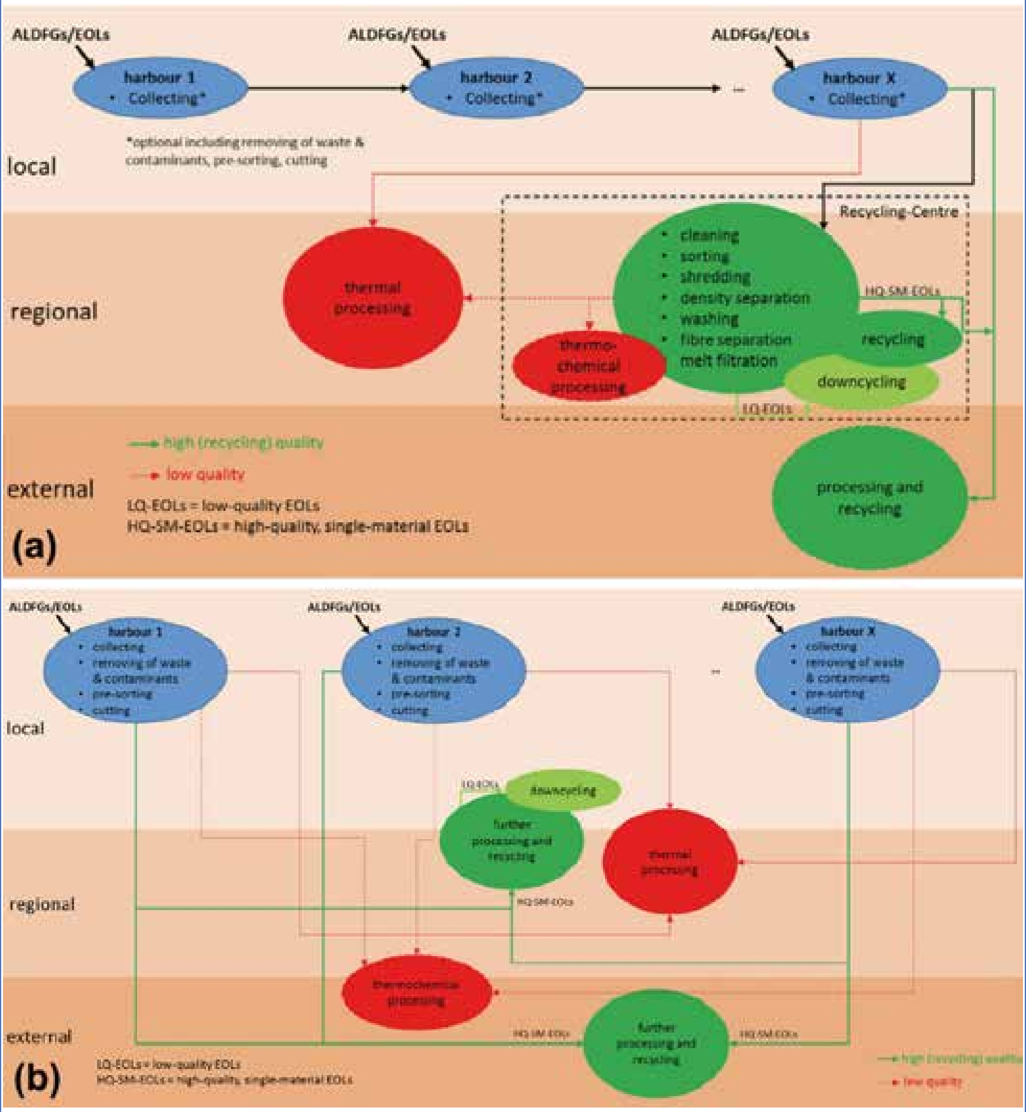
1.3.4 Centralized and decentralized waste management infrastructure

Following the collection of unwanted gears for recycling, often through the provision of port reception facilities (PRFs) – if available and adequate – the pre-processing and transport of unwanted gears to the nearest and best available recycling processing facility is required. The location of this waste management infrastructure is an important technical consideration in fishing gear recycling, as the location influences logistics, resources and costs necessary for the unwanted gears to be delivered to the recycling facility.

The locations of the waste management infrastructure are often referred to as being either "centralized" or "decentralized" (Bertling and Nühlen, 2019). Under a **centralized** infrastructure approach, once enough unwanted fishing gear is collected at a series of available ports to ensure the minimum supply for recycling, these gears are collected via a "collection tour" from the harbours/ports and transported to a centralized regional processing facility (often referred to as a "Recycling Centre"). Here, all pre-processing steps can be undertaken including shredding (for primary to tertiary processes), density filtration and melting (for primary and secondary processes) (Figure 12a) (Bertling and Nühlen, 2019). As indicated by the asterisk in Figure 12a, some basic early recycling pre-processing stages can also take place at the harbours/ports where gears are collected, such as waste and contaminant removal, pre-sorting and cutting. However, most of the pre-processing procedures take place at the centralized processing facility/recycling centre. The final recycling stages can

[15] Indirect waste fees are explained in greater detail in Section 2.1.6: Market-based instruments. Under indirect waste fee systems, the costs associated with port waste disposal facilities are included in broader, pre-established fees that vessels pay to use ports. As a result, fishers are not charged directly to deliver their wastes, but rather these costs are included indirectly through other more general port fees.

FIGURE 12. (A) CENTRALIZED (I.E. RECYCLING CENTRE) AND (B) DECENTRALIZED (I.E. PROCESSING *IN SITU*) WASTE MANAGEMENT INFRASTRUCTURE APPROACHES



Source: Modified and adapted from Bertling and Nühlen (2019). Study on logistics and infrastructure required for DFG treatment. Interreg Baltic Sea Region Programme 2014-2020, MARELITT Baltic Project report (https://marelittbaltic.eu/documents).

either take place at the same central facility, or, if specialized technologies are required (e.g. regranulation, depolymerization, some thermal processing), the fully pre-processed materials may be transported to a specialized facility ("external" in Figure 12a) for processing and recycling.

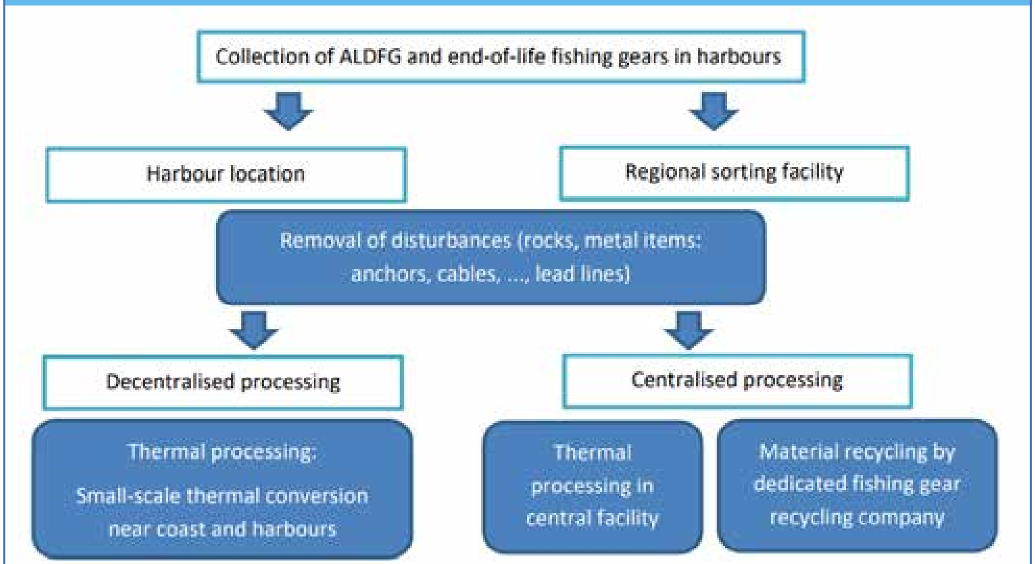
Decentralized waste management infrastructure differs from centralized infrastructure in that rather than having a central processing facility/recycling centre where most pre-processing procedures are undertaken, the early pre-processing procedures for unwanted fishing gears are undertaken at the harbours/ports where they are collected, before being transported to local or regional recycling facilities for the necessary further processing and recycling (Figure 12b; Bertling and Nühlen, 2019). Like centralized infrastructure, if specialized technologies are required, then the nearly fully processed gears may be transported to a specialized facility for final processing/recycling (Figure 12b). In essence, centralized waste processing facilities are referred to as such primarily because of their centralized location in the regional processing facility/recycling centre, whereas decentralized infrastructure can exist on both local and regional levels, with the opportunity for multiple smaller processing and recycling facilities closer to the harbours/ports where gears are collected.

A mix of centralized and decentralized waste management infrastructure and logistics has been advocated for unwanted fishing gear, to allow for optimum and cost-efficient processing (Stolte *et al.*, 2019). To reduce costs, material collection and transportation to disposal or recycling facilities must be organized with the least amount of transportation possible. Both EOLFG and recyclable, clean, single-polymer ALDFG should be collected in separate containers and transported separately from low-quality and mixed ALDFG, which is likely to require further treatment for recycling and possibly different techniques (e.g. tertiary or quaternary processes). Early pre-processing, such as the removal of bulky metal objects and rocks from EOLFG and ALDFG, should be undertaken at or near the receiving harbours to reduce transportation costs. The separation of clean, single-polymer materials from low-quality mixed ALDFG can also take place early in the recycling process, ideally at the fishing port.

A specific unwanted fishing gear collection point can be designated in a regional harbour to collect these materials from across the region, before they are sent to mechanical (primary and secondary recycling), chemical (tertiary recycling) and/or thermal processing (tertiary and quaternary recycling) facilities. It is crucial to centralize and scale the material sorting and dismantling of fishing gear wherever possible, as well as to identify and provide sizeable numbers/volumes of EOLFG and recovered ALDFG. A specialized sorting site may be more efficient and produce more consistent material fractions available for recycling, when compared to the time and financial resources required by local fishers to separate high- and low-quality materials in each port.

After sorting, high-quality single polymer EOLFG and extremely clean, single-material ALDFG can be delivered to a mechanical or chemical recycling plant. Because the cleaning, separation of residual sediments and salts, as well as blending or extruding into recyclates or yarns all require specialist technology and fibre-processing facilities, a centralized infrastructure approach is typically adopted (Figure 13). Thermal

FIGURE 13. CENTRALIZED AND DECENTRALIZED PROCESSING OPTIONS FOR ALDFG AND EOLFG WASTE MANAGEMENT



Source: Adapted from Stolte *et al.* (2019). A treatment scheme for derelict fishing gear. Interreg Baltic Sea Region Programme 2014-2020, MARELITT Baltic Project report (https://marelittbaltic.eu/documents).

processing facilities can be both centralized (if more specialized technologies are required) or decentralized (Figure 13). Central thermal processing plants and other regional material sorting facilities should be strategically positioned near ports and require relatively minimal transportation distances. Decentralized thermal processing facilities are usually practical if only a few tonnes of unwanted fishing gear are processed annually. If small-scale, container-type pyrolysis or steam-reforming facilities are built (see Annex 1.2 for more details on these thermal conversion technologies), these facilities could be positioned between several neighbouring fishing ports to minimize transportation costs and improve the overall efficiency of these recycling processes, depending upon total materials received for recycling.

Each region will need to assess its recycling needs and associated logistics for required centralized and/or decentralized infrastructure. The assessment can be undertaken through a variety of relevant fisheries and waste management stakeholders, local government(s), or a Producer Responsibility Organization (PRO) under an Extended Producer Responsibility (EPR) scheme (see Section 1.3.6 for discussion of EPR for fishing gears). Ultimately, the logistics of fishing gear collection and recycling must be economically sustainable, and the costs of material transportation to these facilities, including carbon emissions from the collection, transportation, preparation and recycling activities, should be assessed.

1.3.5 Market-based instruments

Market-based instruments (MBIs) are tools and technical measures, including management policies and regulatory measures, which influence the cost or market price of a product or a service (Ten Brink *et al.*, 2009). They are largely informed by the 'polluter pays' principle, the 'user/beneficiary pays' principle and the principle of full-cost recovery (Ten Brink *et al.*, 2009). They can be employed to incentivize or disincentive behaviours, and to influence the price of and raise revenue for a good or service. In this way, MBIs offer a suite of mechanisms to support fishing gear recycling through incentivizing and rewarding recyclable fishing gear designs; the inclusion of recycled materials in new gears (or creating disincentives for not including recycled materials in gears); and incentivizing and rewarding the return and collection of unwanted fishing gear for recycling. Finally, they can raise revenues (e.g. for local waste management agencies, port authorities and recycling companies) to support fishing gear recycling infrastructure.

A variety of MBIs can be employed to support fishing gear recycling. Some of these include:

- fishing gear "buy-back" programmes (also commonly referred to as reward schemes);
- deposit-refund schemes;
- registration and deposit systems;
- extended producer responsibility (EPR) schemes;
- taxes, such as environmental taxes, to raise revenue to support recycling logistics and infrastructure;
- "indirect" (also known as "no-cost" or "no-special fee") port waste fees (Brodbeck, 2016; Ten Brink *et al.*, 2009); and
- certification schemes.

Fishing gear "buy-back" programmes, or **reward schemes**, incentivize the return and collection of unwanted gears for eventual recycling by providing financial returns for unwanted fishing gears and other plastic waste returned from fishing operations and the marine environment. For example, in 2001, the Republic of Korea introduced a compensation "buy-back" programme for fishers who removed nets and other marine litter and later 'sold' them back to this programme upon returning to port. Part Two

Section 2.1.6 "Market-based instrument (MBI) example for unwanted fishing gear recovery and collection: *Marine debris buy-back programme in the Republic of Korea*" provides a practical example of this type of MBI.

Deposit-refund schemes require consumers to pay a deposit for items purchased, such as the purchase of fishing gear. This deposit is then refunded to the individual who returns these items at the end of their use. Deposit-refund schemes can occur at the national, regional, or local/municipal levels (Lavee, 2010). Costs associated with implementing such programmes are proportional to the amount of material returned. Deposit-refund schemes for fishing gears should be flexible enough to allow for the return of gears that have been repaired throughout their lifetimes, or combined with other gears, with enough locations available to fishers to support such schemes (Brodbeck, 2016). Careful enforcement is required for both buy-back programmes (reward schemes) and deposit-refund schemes, to reward the responsible collection and return of ALDFG and EOLFG, while avoiding any possible deliberate theft of fishing gears to claim the rewards or refunds.

Registration and deposit schemes are similar to deposit-refund schemes but differ in their requirement to register fishing gears when purchased so that the gear can be identified to its owner. A deposit is paid for the purchase of the gear, which can then be earned back by the owner when they return the gear at the end of its life (Bertling and Nühlen, 2019). These systems can additionally support fishing gear marking systems (Section 1.3.2.1) and Extended Producer Responsibility (EPR) schemes. The latter, which are discussed in greater detail in Section 1.3.6, can support fishing gear recycling by ensuring that the fishing gear manufacturers/producers are responsible for returning fishing gears for recycling at their end of life.

Taxes, such as environmental taxes, are an example of a cross-cutting MBI that might complement or support other MBIs such as EPR and reward schemes. Taxes are viewed by many economists as a successful type of MBI by virtue of their ability to discourage polluting behaviour and the inefficient use of resources, while generating revenue with relatively modest implementation costs (Oosterhuis *et al.*, 2014). Taxes may be imposed at several stages of the fishing gear production process, including the manufacturing, assembly and purchasing stages. The revenue from taxes imposed on different stages of gear production and purchase can be used to finance gear management and end-of-life stewardship, such as supporting the financing of unwanted fishing gear recovery, collection and recycling infrastructure. It is important to define clear requirements and obligations for the funds raised from these taxes to ensure that they are effectively utilized to establish and pay for the relevant recycling systems or infrastructure. Taxes can also be lowered to incentivize certain production behaviours and the use of, for example, more recyclable materials in fishing gear production.

"Indirect" waste fees have also been put forward as a way of encouraging the collection and return of unwanted fishing gears to ports. Under indirect fee systems, vessels pay a pre-established amount in advance to use the ports, including waste facilities. This is in contrast to "direct fees", where vessels pay additional costs to deliver their waste. Indirect fee systems can incentivize vessels to dispose of their unwanted gears at ports because the cost of this waste delivery is already included in their payment to use the port, irrespective of whether they take advantage of the facilities and regardless of the amount of unwanted gears and other waste they deliver (Brodbeck, 2016). As discussed in Section 1.3.3 on port reception facilities, clear communication with vessels and fishers is required to ensure they are aware of the availability of waste reception facilities, and that they will not incur any additional fees to deliver their wastes.

Ecological and social standards, **certification schemes** and labelling guidelines, which are often used in the fisheries context to identify sustainable fisheries and promote good environmental and social practices also have the potential to incentivize fishing gear recycling. Certification and labelling schemes and standards can incentivize the use of recycled plastics in products, while certification schemes for fisheries can display and encourage responsible fishing gear stewardship including end-of-life return for recycling. While certification schemes are not always categorized as MBIs,[16] they are included in this report because of their relevance and the opportunity to provide information to consumers about responsible fishing gear use by fishing companies. Certification schemes have the potential to motivate responsible gear design, use and end-of-life stewardship according to established standards, as well as support recycling through, for example, standards for the return of recovered ALDFG and EOLFG. They can also influence consumers to support responsible fishing-gear-certified products. The latter can include fish caught by certified fishers and companies, or products using recycled fishing gear materials from certified suppliers. Some organizations such as the Marine Stewardship Council and Aquaculture Stewardship Council, among others,[17] have begun to incorporate certification standards to address and minimize ALDFG and/or ghost gear (EIA, 2022; Hodgson, 2022; Huntington, 2019; MSC, 2022). Existing certification standards for ALDFG and ghost gear could be updated to include considerations around, and requirements for, the recycling of end-of-life fishing gear. New certification standards could also be created where none currently exist. For example, the *Redes de America* programme is working on a certification model for fishing gears based on mass balance; they anticipate the programme will encourage companies to address the fishing gear recycling issue more effectively, and provide valuable information to seafood consumers (more information about this work is included in Section 2.1.3).

Table 3 summarizes factors to consider before selecting a MBI. These factors can also be used in the context of selecting MBIs aimed to promote fishing gear recycling.

TABLE 3. FACTORS TO CONSIDER BEFORE SELECTING A MARKET-BASED INSTRUMENT (MBI)

Factor	Description
1. Feasibility	Does the MBI address: national environmental problems and priorities, national obligations, international objectives?
2. Effectiveness	Does the economic instrument have the potential to offer significant environmental benefits? Is the instrument cost-effective (administrative, implementation, monitoring etc.)?
3. Financial benefit	Will the MBI raise useful revenue (e.g. revenue that supports sustainability of the MBI system with funds benefitting, in the case of this report, fishing gear recycling systems)?
4. Fairness	Is the MBI fair and equitable (i.e. 'polluter pays' principle)?
5. Social impacts	What are the impacts across different income/social groups? Will the target audience be able to afford the associated expenses?
6. Pricing	Does the instrument lead to efficient pricing (improving market price to become closer to resource/social pricing)?
7. Enforcement	Are there policy, administrative and infrastructural frameworks that will support the MBI? Are there barriers?
8. Acceptability	Is it understandable and credible to the stakeholders and public?
9. Economic consistency	How does the MBI interact with the budget deficit, competitiveness, inflation etc.? In the case of this report, economic consistency includes long-term MBI sustainability, including practicality and use.

Source: Modified and adapted from Brodbeck (2016). Mechanisms to support the recycling/reuse of fishing gear and the prevention of gear becoming lost/abandoned at sea. Barrier assessment. Circular Ocean Report Type 10-2016. NTNU, Norwegian University of Science and Technology. Trondheim, 5 October, 2016. Information from Ten Brink *et al.* (2009). Guidelines on the Use of Market-based Instruments to Address the Problem of Marine Litter. Institute for European Environmental Policy (IEEP), Brussels, Belgium, and Sheavly Consultants, Virginia Beach, Virginia, USA.

16 Froger *et al.* (2015) discuss the relevance of eco-labels and certification schemes within MBIs, given that producers engage voluntarily and commit themselves to established environmental criteria and standards, and that the premium prices commanded by certified products can be interpreted as payments for the maintenance or supply of ecosystem services. **Froger, G., Boisvert, V., Méral, P., Coq, J.-F. L., Caron, A. & Aznar, O.** 2015. Market-Based Instruments for Ecosystem Services between Discourse and Reality: An Economic and Narrative Analysis. *Sustainability* [Online], 7, 10.3390/su70911595, 11595–11611 pp.

17 See pag. 4 of EIA (2022) on certification bodies and eco-labels.

1.3.6 Extended Producer Responsibility (EPR) for fishing gears

As discussed in Section 1.3.5, the Extended Producer Responsibility (EPR) principle can be used as a market-based instrument to support fishing gear recycling. This section broadly describes EPR as a principle, as well as some of its applications to support the management of unwanted fishing gear and fishing gear recycling.

Extended Producer Responsibility (EPR) is an environmental principle that makes producers responsible for the entire life cycle of the products that they introduce on the market: from their design until end of life, including waste collection and recycling. The EPR principle emerged through the analysis of experiences from recycling and waste management systems, and the implementation of policy instruments to promote cleaner production (Lindhqvist, 2000).

A formal definition of EPR was presented by Lindhqvist (1992):

> Extended Producer Responsibility is an environmental protection strategy to reach an environmental objective of a decreased total environmental impact from a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal of the product. The Extended Producer Responsibility is implemented through administrative, economic and informative instruments. The composition of these instruments determines the precise form of the Extended Producer Responsibility.

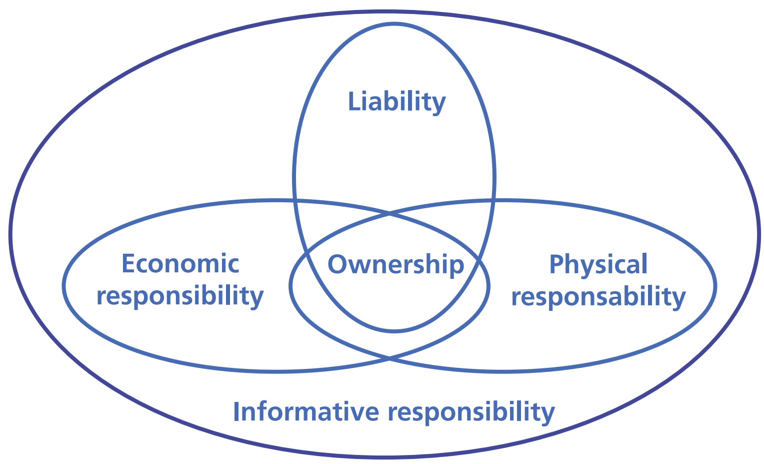
The "polluter pays" concept is consistent with the EPR principle, which is also a prerequisite for including the required life-cycle costs of a product in the price (WWF and IEEP, 2020). Figure 14 distinguishes different forms of responsibility under EPR schemes.

Liability is the responsibility for the product's demonstrable impact on the environment. Legislation determines the scope of the responsibility, which may cover several stages of the product's life cycle, including its use and eventual disposal.

Economic responsibility refers to the producer's commitment to paying all or a portion of the costs associated with, for example, the collection, recycling, or disposal of the products they manufacture.

Physical responsibility is a term used to describe systems where the manufacturer is active in the physical management of the products and/or their impacts.

FIGURE 14. FORMS OF RESPONSIBILITY UNDER EXTENDED PRODUCER RESPONSIBILITY (EPR) SCHEMES



Source: Modified and adapted from Lindhqvist (2000). Extended Producer Responsibility in Cleaner Production: Policy Principle to Promote Environmental Improvements of Product Systems. International Institute for Industrial Environmental Economics (IIIEE), Doctoral Dissertation, Lund University.

Additionally, the manufacturer could retain the ***ownership*** of the products produced for the duration of their life cycles, making the manufacturer accountable for any environmental impacts the products may cause. In the case of fishing gears, assigning ownership to the fishing gear manufacturer is challenging as the manufacturer/ producer often has very little to no control over how fishers use the gear produced in the marine environment.

Informative responsibility refers to a variety of ways to increase responsibility for the products created by compelling manufacturers to provide details about the products' properties.

As a policy principle, EPR is important to

> promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product (OECD, 2001).

Different policy tools can be employed to support EPR schemes, including those that can support fishing gear recycling. These include product (e.g. fishing gear) take-back requirements, economic and market-based instruments (see Section 1.3.5), regulations and performance standards for fishing gear production, and information-based instruments concerning the material composition of fishing gear and the requirements for end-of-life management (WWF and IEEP, 2020).

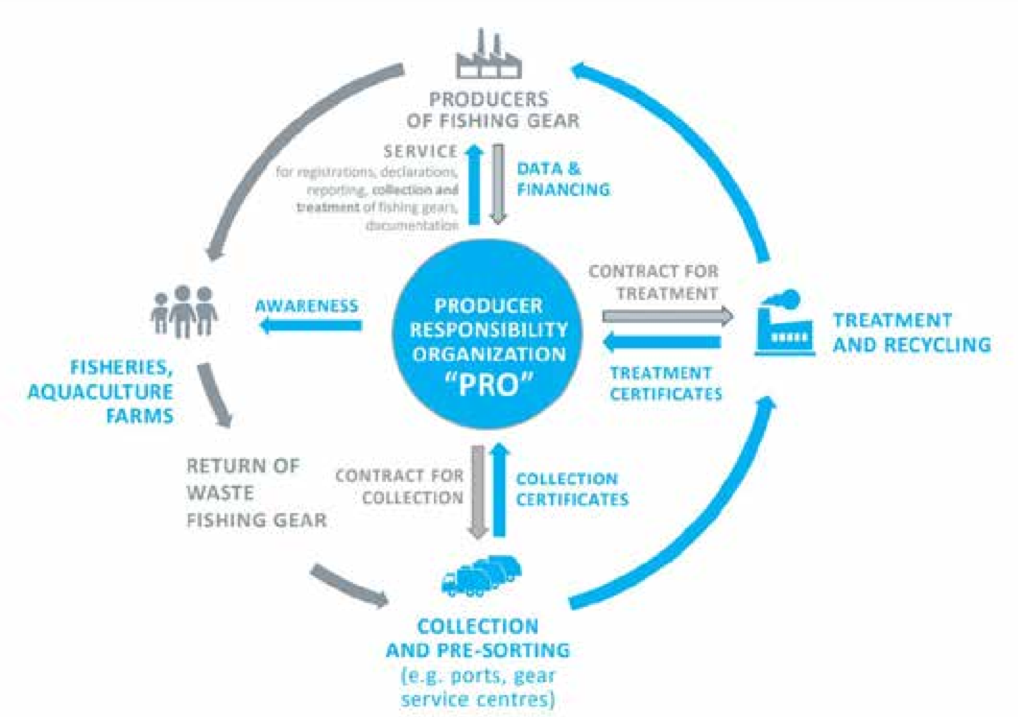
Under EPR schemes, producers of fishing gear will cover costs related to the separate collection of unwanted fishing gears that are delivered to port reception facilities or equivalent collection systems, in addition to their subsequent transport and treatment for repurposing, recycling, incineration or landfilling. It is highly recommended that policymakers and government agencies design EPR programmes in consultation with stakeholders; these include fishing operators, manufacturers and assemblers of fishing gear, recyclers, small and medium enterprises (SMEs), entrepreneurs, co-operatives or social enterprises. According to Charter *et al.* (2020), this flexibility gives states the opportunity to consider other policy approaches, in order to:

- reward fishing operators, fishing gear manufacturers, or other parties who repair or reuse existing fishing gear components, taking into account maximum gear and component lifetimes;
- penalize the disposal of recyclable fishing gear in landfills and incinerators; and
- at a local and national level, offer incentives to stakeholders in the wider innovation system.

The adoption of EPR schemes and policies can promote changes towards more recyclable fishing gear designs, as well as improved functionality, by giving fishing gear producers and manufacturers full physical and financial responsibility for the products – full gear items and gear components – they produce (Lindhqvist, 2000). Moreover, EPR policies and schemes offer a suite of financial options to governments and policymakers looking to raise the country or region's recycling and waste management standards. For example, the revenues generated through EPR schemes can be used by local governments, port authorities and waste management agencies to support fishing gear recycling programmes: these may include port collection, pre-processing, transport and eventual recycling.

Many EPR schemes have separated the roles of government, policymakers and regulators to establish and enforce EPR regulations. This means that producers, distributors and users are responsible for end-of-life product collection and implementing a recycling scheme, such as through a Producer Responsibility Organization (PRO). A PRO can also set differentiated fees for each type of product

FIGURE 15. EPR SCHEME FOR FISHING GEAR



Source: Adapted from Zych (2020). Extended Producer Responsibility Schemes - What role for fishing gear producers? Landbell Group. Available at https://webgate.ec.europa.eu/maritimeforum/en/system/files/landbell_aneta_zych_epr_schemes.pdf.

that producers are liable to pay EPR costs for. Figure 15 provides an example of the roles of various stakeholders under an EPR scheme for fishing gear run collectively through a PRO.

The Advocating Extended Producer Responsibility for fishing gear position paper (IUCN *et al.*, 2021) provides a series of recommendations to be considered by authorities and other relevant stakeholders for setting up EPR policies and schemes for fishing gear and ropes. The recommendations are:

1. apply a staged approach;
2. clearly define legal terms related to EPR for fishing gear and ropes;
3. conduct coordinated design and implementation at national, local and international level;
4. consider Platform-based design and implementation of EPR schemes;[18]
5. create and strengthen governance mechanisms;
6. management and distribution of funds;
7. address jurisdiction challenges;
8. develop financial schemes and instruments that support effective implementation of EPR for fishing gear and ropes;
9. design effective implementation plans for EPR;
10. implement regular monitoring and evaluation; and
11. engage key stakeholders (IUCN *et al.*, 2021).

The European Union's Single Use Plastics (SUP) Directive (EU) 2019/904 (2019) provides an example of how EPR can be applied to fishing gear at the regional scale.

[18] This includes, for example, regional or thematic platforms such as the European Union or specific international organizations that align policies and guidelines, in addition to risk assessments and management recommendations by organizations such as the Global Ghost Gear Initiative (GGGI).

The SUP directive requires Member States to create specific EPR schemes for fishing gear containing plastics; it includes any item or piece of equipment that is used in fishing or aquaculture, including fishing gear components that contain plastic. Under the SUP Directive, producers will be financially responsible for the full life cycle of their gears and gear components containing plastic , including raising awareness around waste management options at the end of a gear's life, namely: end-of-life collection, transport and final treatment, and including recycling if this is an option/possibility. Because of the diversity of actors involved in fishing gear production (e.g. producers, assemblers, gear repairers, importers and sellers), defining the producer's responsibility under these EPR schemes constitutes a challenge within the region. Harbours, fishers and small-scale fishing gear producers are excluded from these product responsibility requirements under the SUP Directive.

1.3.7 International policy instruments related to unwanted fishing gear

International policy and regulatory instruments can additionally be employed to support unwanted fishing gear recycling, to complement and further support the technical measures discussed in Sections 1.3.1–1.3.6. A wide range of international policy instruments exist that address unwanted fishing gear. The publication *Legal aspects of abandoned, lost or otherwise discarded fishing gear* details these international and regional legal and regulatory instruments (Hodgson, 2022). Most existing international law and regulatory instruments relevant to unwanted fishing gear were more broadly designed to address global marine conservation and pollution issues, as well as fisheries management considerations. Because ALDFG is a significant source of sea-based marine plastic litter with adverse impacts on environmental conservation and fisheries sustainability, many of these instruments apply directly and indirectly to unwanted fishing gear, including often specifically ALDFG.

Key international marine litter conventions, protocols, agreements and action plans that apply to unwanted fishing gear are also broadly relevant to the specific topic of fishing gear recycling in terms of support for fishing gear stewardship and responsible end-of-life management. These include, but are not limited to:

- The **United Nations Convention on the Law of the Sea (UNCLOS)** Part XII, which is dedicated to the "Protection and preservation of the marine environment". States are required to take, individually or jointly as appropriate, all measures consistent with UNCLOS that are necessary to prevent, reduce, and control pollution of the marine environment from any source (UNEP, 2016).
- The **United Nations Fish Stocks Agreement (UNFSA)**, as an implementing agreement adopted following UNCLOS to address the conservation and exploitation of highly migratory and straddling fish stocks, with specific reference to minimizing pollution, waste, discards and catch by "lost or abandoned gear" and its associated impacts in article 5. It also contains provisions to support gear marking (article 18) and provide information on a vessel's fishing gear (article 19) (Hodgson, 2022).
- **United Nations General Assembly (UNGA) Resolutions** (variety, including UNGA Resolutions 57/142, 60/31), including for the collection of ALDFG data and sharing information; the analysis of implementation and effectiveness of ALDFG management measures; support for ALDFG studies, including socioeconomic considerations; the development of best management practices and prevention and recovery programmes; and national inventories of net and other gear types (Hodgson, 2022).
- **United Nations Environment Assembly (UNEA) Resolution 5/14** to "End plastic pollution: towards an international legally binding instrument" initiated an international process to negotiate a new international legally binding instrument

to prevent plastic pollution, including in the marine environment, with ambitions to complete negotiations by the end of 2024 (UNEA, 2022).

- United Nations **2030 Agenda for Sustainable Development** supports sustainable development globally through 17 Sustainable Development Goals (SDGs), which aim to end poverty, improve health and education, reduce inequality, spur economic growth, tackle climate change and work to preserve oceans and forests (UNDP, 2016; United Nations, 2023). A variety of SDGs are relevant to fishing gear recycling including specifically SDG 14 Life Below Water, which aims to conserve and sustainably use the oceans, sea and marine resources for sustainable development, with special relevance for target 14.1, which aims to prevent and significantly reduce marine pollution of all kinds, including marine debris. SDG 12 Responsible Consumption and Production, and SDG 17 Partnerships for the Goals are also specifically relevant with respect to the need for collaboration and partnerships among stakeholders to address the full life cycle of fishing gear.
- The **Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal**, with requirements for the environmentally sound management of waste items (UNEP, 2021b).
- The **International Maritime Organization (IMO) International Convention for the Prevention of Pollution from Ships (MARPOL)** including specifically MARPOL Annex V to prevent garbage (which includes fishing gear) from ships. MARPOL is an international legally binding instrument that includes provisions for the prevention of pollution from fishing gears, including in the form of plastic waste. It also supports the provision of adequate port reception facilities for garbage, which can also be used for unwanted fishing gear collection and return (IMO, 2016).
- The **IMO Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter 1972** (also known as the London Convention/London Protocol (LC/LP), which includes provisions that prohibit the dumping of plastic waste and persistent synthetic materials, such as fishing nets and ropes.
- The **IMO Action Plan to Address Marine Plastic Litter from Ships**, includes a variety of measures to prevent and reduce ALDFG, with specific measures concerning the availability and adequacy of port reception facilities, consideration of mandatory fishing gear marking, lost fishing gear reporting, and support for the delivery of unwanted fishing gear to shore facilities (IMO, 2018).
- The Food and Agriculture Organization of the United Nations **(FAO) Code of Conduct for Responsible Fisheries (CCRF)**, which includes the minimization of pollution and catch from lost or abandoned gear, minimization of lost gear and its impacts, and provisions for waste disposal systems for fishing gear (FAO, 1995).
- The **FAO International Guidelines on Bycatch Management and Reduction of Discards**, with provisions to reduce impacts from lost fishing gear including ghost fishing, modification of fishing gear and methods, identification of gear ownership, and gear retrieval (Hodgson, 2022).
- The **FAO Voluntary Guidelines on the Marking of Fishing Gear (VGMFG)**, which include general principles and guidance for fishing gear marking and owner identification, a framework for undertaking risk assessments for gear marking, measures to prevent, reduce and recover ALDFG, including specific references for gear recycling, and broad support for related fishing gear management measures. The VGMFG and how they link to fishing gear recycling is explained in greater detail in Section 1.3.2.

These global conventions, protocols and agreements which address marine litter, pollution and fisheries management issues, and which specifically include ALDFG, are transposed by countries participating at the global level into analogous legal instruments at the regional and national levels. These international policies and regulatory instruments have been included in this report as they are broadly relevant to fishing gear recycling as an option for responsible end-of-life fishing gear management. The prevention, reduction and mitigation measures covered by many of these international instruments affect the quality and quantity of fishing gears that can be available for recycling in many ways, in addition to the overarching fishing gear stewardship principles that gear recycling helps to support.

Actions to address ALDFG, including those that support unwanted fishing gear management and recycling more specifically, can also be undertaken at the regional level to promote cooperation and coordination among countries with shared marine resources. This can include actions undertaken by a variety of regional management and policy organizations and bodies, including regional fisheries management organizations (RFMOs), regional fishery bodies (RFBs) more broadly, as well as through regional seas organizations and programmes. A variety of RFMOs have adopted measures to address ALDFG. This includes mandatory lost fishing gear reporting under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), and conservation management measures (CMMs) targeting ALDFG under the International Commission for the Conservation of Atlantic Tuna (ICCAT) and the Western and Central Pacific Fisheries Commission (WCPFC) (Hodgson, 2022). Furthermore, the Indian Ocean Tuna Commission (IOTC) is discussing the operationalization of the VGMFG in its area of competence (He and Lansley, 2022).

Regional seas programmes, including through regional seas conventions and action plans (RSCAPs)[19] on marine litter, can additionally support ALDFG actions and interventions and unwanted fishing gear management and recycling efforts (UNEP and Grid-Arendal, 2016). For example, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) is supporting fishing gear recycling efforts and circular economy considerations (OSPAR Commission, 2020). The European Union's Single Use Plastics and Port Reception Facilities directives can serve as additional examples of broader regional policies undertaken to responsibly manage unwanted fishing gears, including the provision of port reception facilities for unwanted fishing gears and supporting fishing gear recycling where practical (Communication COM(2018) 33, 2018; Directive (EU) 2019/904, 2019; European Commission, 2020c).

Given the diversity of different agencies/authorities/sectors that some action plans and regional organizations/bodies can overlap with when addressing ALDFG and fishing gear recycling (e.g. environmental, fisheries, maritime transport and port authorities), it is important to communicate which organizations and agencies will bear responsibility for ALDFG/unwanted fishing gear interventions at both regional and national levels. This includes the monitoring, control and enforcement of these interventions. It is also important to ensure that actions undertaken by different regional agencies and national governments are communicated, aligned and coordinated. Fluid communication and coherence ensures they can support one another more effectively and elevate the impact of their efforts, in light of the diversity of actors and stakeholders engaged with unwanted fishing gear management and fishing gear recycling.

[19] There are 18 regional seas conventions and action plans, six of which are managed directly by UNEP. These include the Mediterranean (Barcelona Convention), Wider Caribbean (WCR), East Asia Seas, Eastern Africa (Nairobi Convention), Northwest Pacific (NOWPAP), and West and Central Africa (WACAF) (UNEP and Grid-Arendal, 2016).

1.4 CIRCULAR ECONOMY RELATED TO FISHING GEAR

This section broadens the discussions regarding fishing gear recycling covered in Sections 1.2 and 1.3 to explore a more inclusive circular economy (CE) approach for fishing gear use and management, from its design and manufacture through to the end of its life. A CE model for fishing gears includes fishing gear recycling as one option in a larger suite of fishing gear life-cycle stages. The intention of the CE approach is to minimize the production of waste and pollution through the gear's life cycle while retaining the value of the fishing gear, including its constituent materials, as long as possible. This section begins with an introduction to the CE model, including how it applies to fishing gears. It then discusses similarities to the Waste Hierarchy and R-based (e.g. 3Rs) circular economy models/concepts, and how they complement the CE model including their application to fishing gears and unwanted gear recycling. It concludes with an exploration of more circular fishing gear design strategies and how business models for fishing gears can become more circular to ensure better market viability of the CE model. The application of CE principles to fishing gear design, manufacture, use and end-of-life management can not only improve opportunities for fishing gear recycling, but can support a more holistic and sustainable life cycle for fishing gears in the long term.

1.4.1 The circular economy model

The circular economy (CE) model is one of the most popular approaches to addressing global concerns over the needs for resource conservation and carbon reduction (Van Fan *et al.*, 2022). A circular economy refers to a production and consumption model whereby final resources are reused and recycled back into the product life cycle as much as is practical, and where waste is ultimately kept to a minimum (Korhonen *et al.*, 2018).

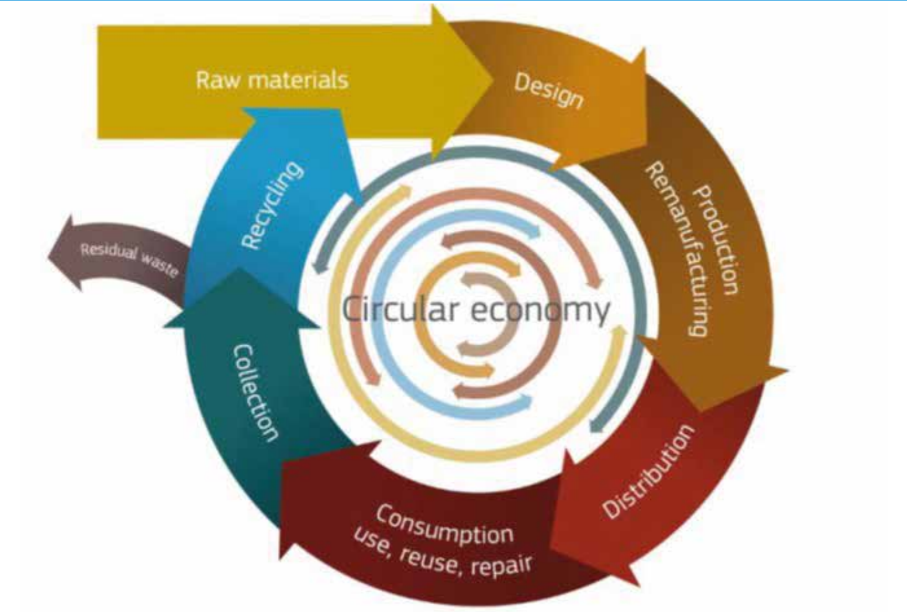
As per (Alhawari *et al.*, 2021), the Circular economy is defined as:

> The set of organizational planning processes for creating and delivering products, components, and materials at their highest utility for consumers and society through effective and efficient utilization of ecosystem, economic, and product cycles by closing loops of concerning resource flows.

A circular economy is regenerative by design and eventually attempts to decouple development from the use of limited resources (Ellen MacArthur Foundation, 2019). The CE model supports efforts that allow materials to retain their worth for as long as possible inside the economy, by being regularly reused. Its principles support new business models, design thinking, and more efficient methods of consumption and production (Di Vaio *et al.*, 2022; Esposito *et al.*, 2018).

The circular economy **seeks to avoid waste and pollution from the beginning of a product's life cycle through the end-of-use stage**. Figure 16 depicts the main stages of a circular economy model (Communication COM(2014) 398, 2008). Each phase offers opportunities for lowering costs and dependence on natural resources, stimulating growth and employment, as well as reducing waste and environmentally harmful emissions. Considering the design of production methods, goods, and services is a crucial first step for CE models. Instead of being designed for relatively short-term use prior to disposal, products may be redesigned to last longer, so that they can be restored, enhanced and remanufactured throughout their life cycle, before being recycled at their end of life.

FIGURE 16. CONCEPTUAL DIAGRAM OF THE KEY PHASES IN A CIRCULAR ECONOMY MODEL



Source: Adapted from Communication COM(2014) 398 (2008). Towards a circular economy: a zero waste programme for Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2014) 398 final.

While the design stage can include design for gear recyclability (Section 1.3.1), the disposal stage of a product's lifespan is where the actual recycling process begins. However, recycling will not be adequate to offset the massive volume of waste that is currently and increasingly created, and which exacerbates present environmental challenges. In the case of plastics, less than 10 percent of plastics are thought to have re-entered the value chain since the 1950s, i.e. been recycled or reused (Geyer, 2020; Geyer *et al.*, 2017). According to the World Economic Forum:

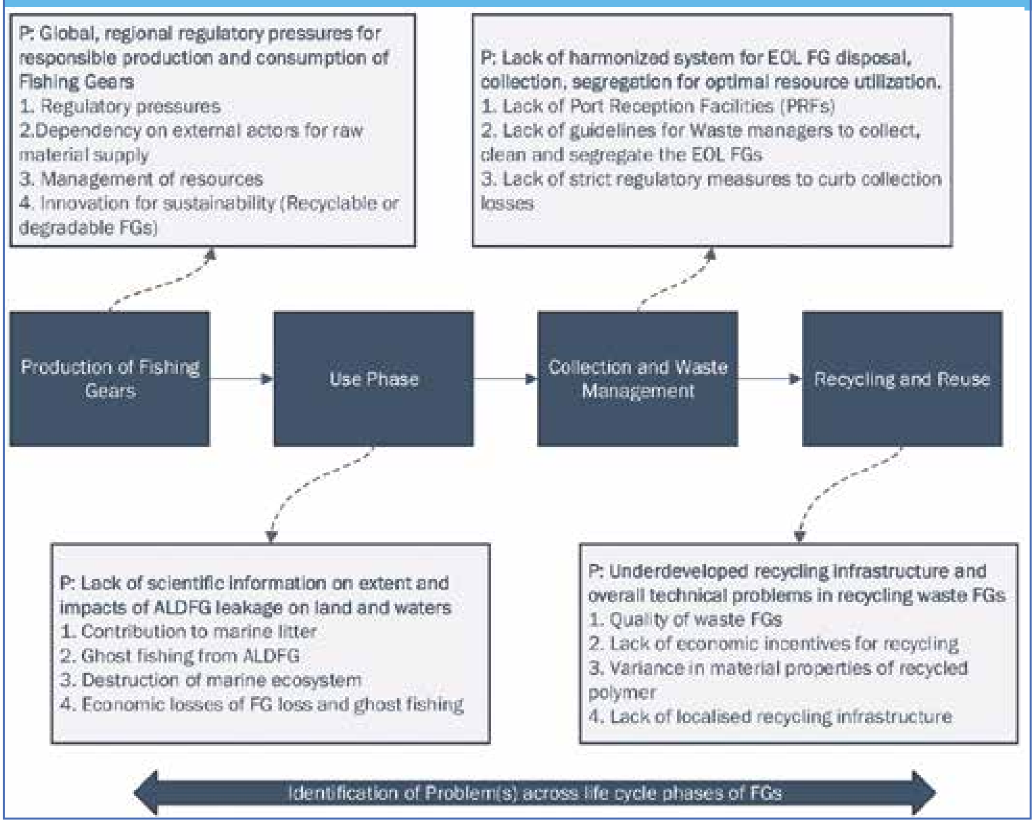
> In a properly built circular economy, one should rather focus on avoiding the recycling stage at all costs. It may sound straightforward, but preventing waste from being created in the first place is the only realistic strategy (World Economic Forum, 2017).

While recycling is undoubtedly important, under a circular economy approach it is all the more important to ensure that products and materials are designed to be reused, repaired, and remanufactured from the start. Companies are already studying ways to 'design out' waste when goods are still at the concept stage (World Economic Forum, 2020).

Studying life-cycle phases is vital to enabling knowledge around circularity, including the key phases in a circular economy model for fishing gears. The application and practice of a life-cycle approach for fishing gears will require stepwise approaches across the entire life cycle of the gear. Figure 17 provides examples of problems identified across the life-cycle phases of fishing gear, while Figure 18 suggests elements for evaluation and associated strategies across the fishing gear life-cycle phases. Informed by a systems engineering methodological framework, these figures approach the complex resource management issue of ALDFG from a fishing gear life-cycle perspective (Deshpande and Haskins, 2021).

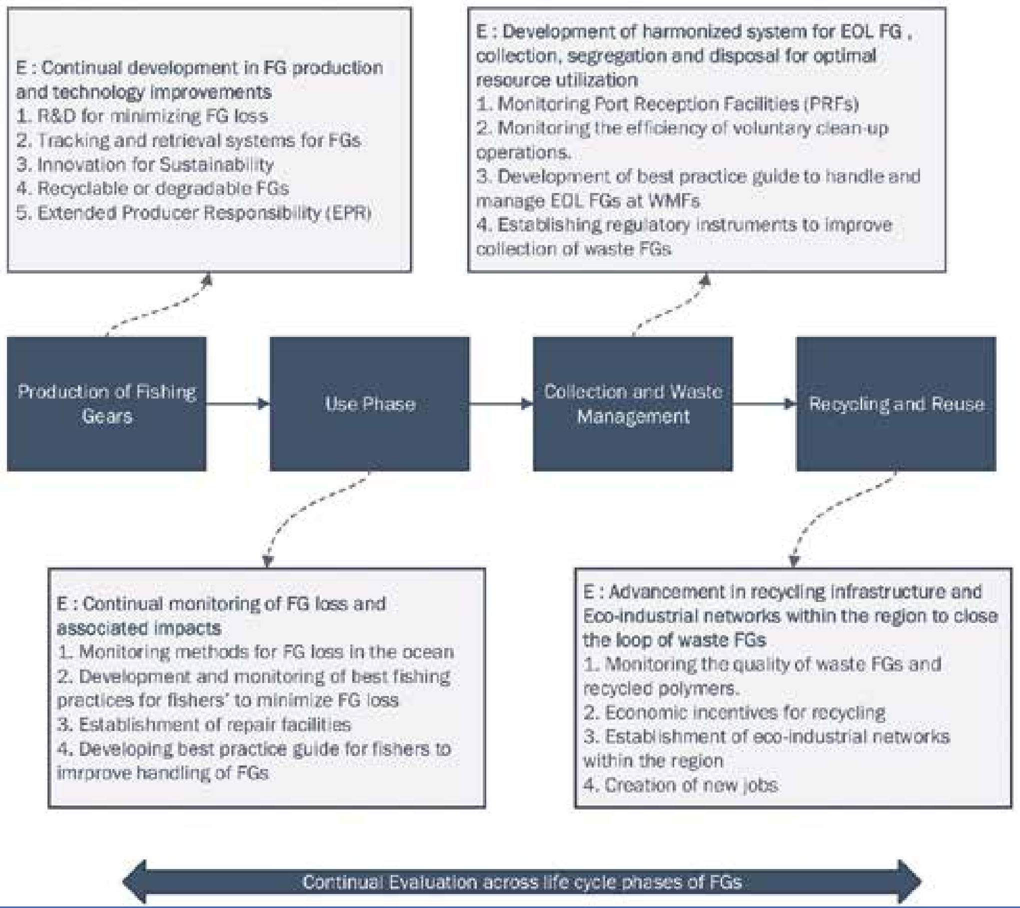
The reduction of waste pollution and the **creation of a CE require complex actions by several stakeholders**. These include government agencies, consumers, retailers, waste management organizations, waste recyclers, and others, including the informal sector (e.g. waste pickers at landfill sites) (Hahladakis, 2020; UNEP, 2021b). Creating an effective CE that is accepted by businesses and the public requires numerous stages, including introducing appropriate infrastructure and investment, and facilitating behavioural change throughout the supply chain (UNEP, 2016). The first stage in establishing a national CE policy typically requires the establishment of a legislative standard for circularity. Other stages can include: increasing the use of renewable energy in the manufacturing of materials; employing recycling and demand-management techniques; substituting alternatives for fossil fuels as plastic feedstock; enhancing design and recycling standards (see Sections 1.3.1 and 1.4.3); lowering the number of hazardous additives in plastic products; valuing the cost of plastics more accurately; strengthening infrastructure for the management of waste; raising public awareness; and switching to reuse-based business models (Dauvergne, 2018; Forrest *et al.*, 2019; Zheng and Suh, 2019).

FIGURE 17. PROBLEMS IDENTIFIED ACROSS THE LIFE-CYCLE PHASES OF FISHING GEAR



Source: Adapted from Deshpande and Haskins (2021). Application of systems engineering and sustainable development goals towards sustainable management of fishing gear resources in Norway. Sustainability, 13(9), 4914.

FIGURE 18. CONTINUOUS EVALUATION STRATEGIES SUGGESTED FOR FISHING GEAR RESOURCES ACROSS THE LIFE-CYCLE PHASES SYSTEM



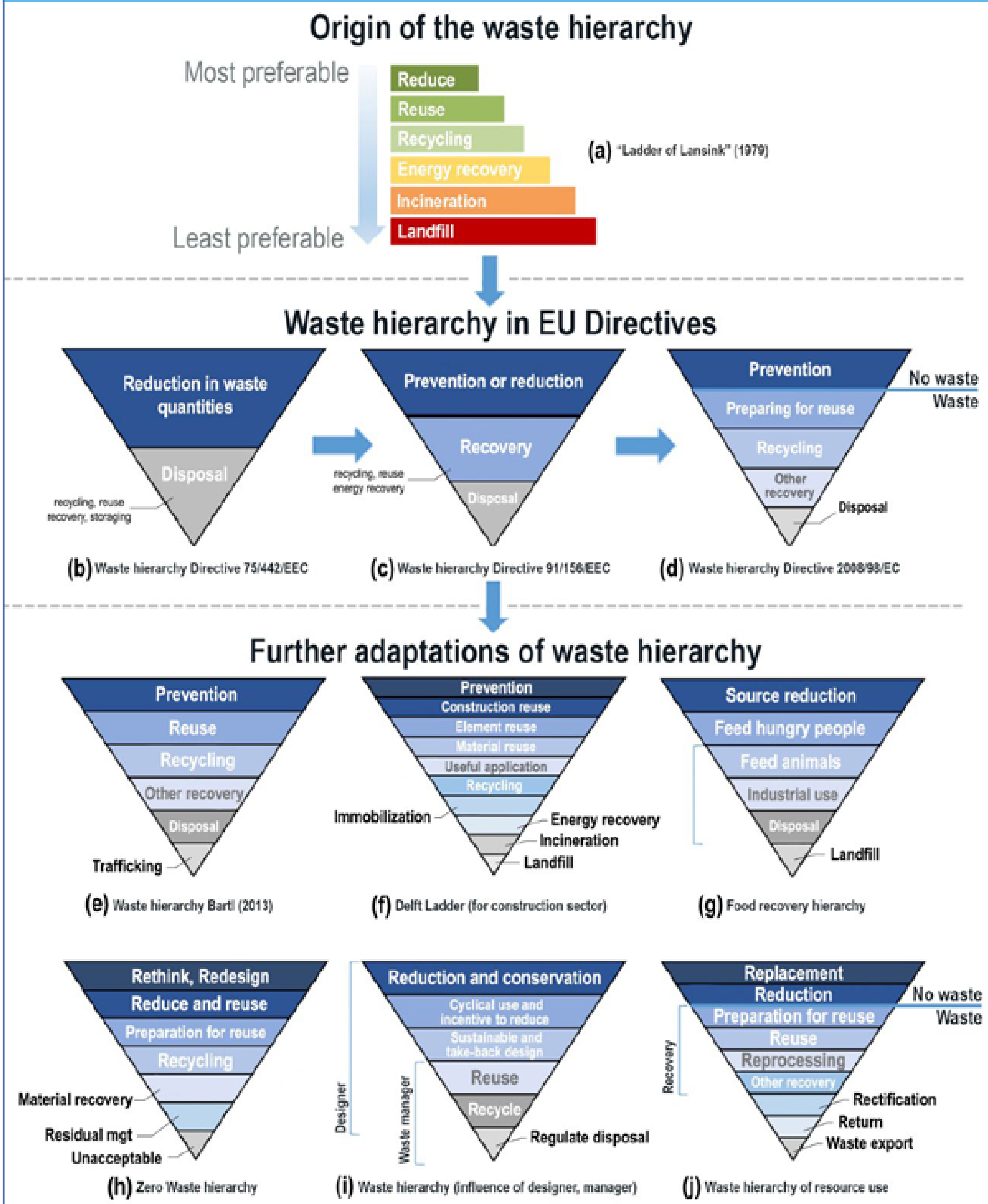
Source: Adapted from Deshpande and Haskins (2021). Application of systems engineering and sustainable development goals towards sustainable management of fishing gear resources in Norway. Sustainability, 13(9), 4914.

Although awareness of the importance of the CE is growing in economic sectors, the **lack of research on the profitability of CE approaches** presents the main obstacle towards implementation. Therefore, CE financing strategies, new business models and viable markets need to be studied further (see Section 1.4.4). Future research is needed on how existing methods, such as life-cycle analyses (LCAs), material flow analyses (MFAs) and cost-benefit analyses (CBAs) can be applied and adapted to different CE contexts. Such research will enhance conceptual knowledge as well as the empirical and quantitative understanding of the link between circular economies and sustainable economies (Rezaie *et al.*, 2022).

1.4.2 The waste hierarchy and R-based circular economy concepts

While the CE has been adopted as the overarching paradigm for resource and waste management in several studies, few of these studies also include discussions of the waste hierarchy. The waste management hierarchy identifies a preferred sequence of actions for waste reduction and management. The waste hierarchy seeks to **create the least amount of waste while maximizing the practical advantages from waste items** (Egüez, 2021). A fundamental principle of the waste management hierarchy is known as the *"Ladder of Lansink"* (Lansink, 1979, 2018), which highlights the order of preference for waste management and resource conservation options, with "reduce" at the top and "landfill" at the bottom. A basic schematic representation of the ladder is provided in Figure 19(a).

FIGURE 19. DEVELOPMENT OF WASTE HIERARCHY IN EUROPE



Notes: Panel (a) is based on the ladder of Lansink (1979); (b) is designed based on the Council Directive 75/442/EEC (1975); (c) is plotted based on the Council Directive 91/156/EEC (1991); (d) is pictured based on the Directive 2008/98/EC (2008); (e) is derived from Bartl (2013); (f) is from Hendricks and Te Dordthorst (2001); (g) is from the US Environmental Protection Agency's Food Recovery Hierarchy (Ceryes *et al.*, 2021); (h) is redesigned based on Zero Waste Hierarchy (Simon, 2019); (i) is from Cole *et al.* (2019); (j) is a "hierarchy of resource use" proposed by Gharfalkar *et al.* (2015).

Source: Modified and adapted from Zhang *et al.* (2022). An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Science of The Total Environment, 803, 149892 (https://doi.org/10.1016/j.scitotenv.2021.149892).

The Waste Hierarchy is largely enforced in Europe under the Waste Framework Directive (WFD) of 2008 (Directive 2008/98/EC, 2008). Prior to the Waste Framework Directive of 2008, globally the notion of the waste hierarchy was only found in environmental literature and the environmental legislation of some European Union

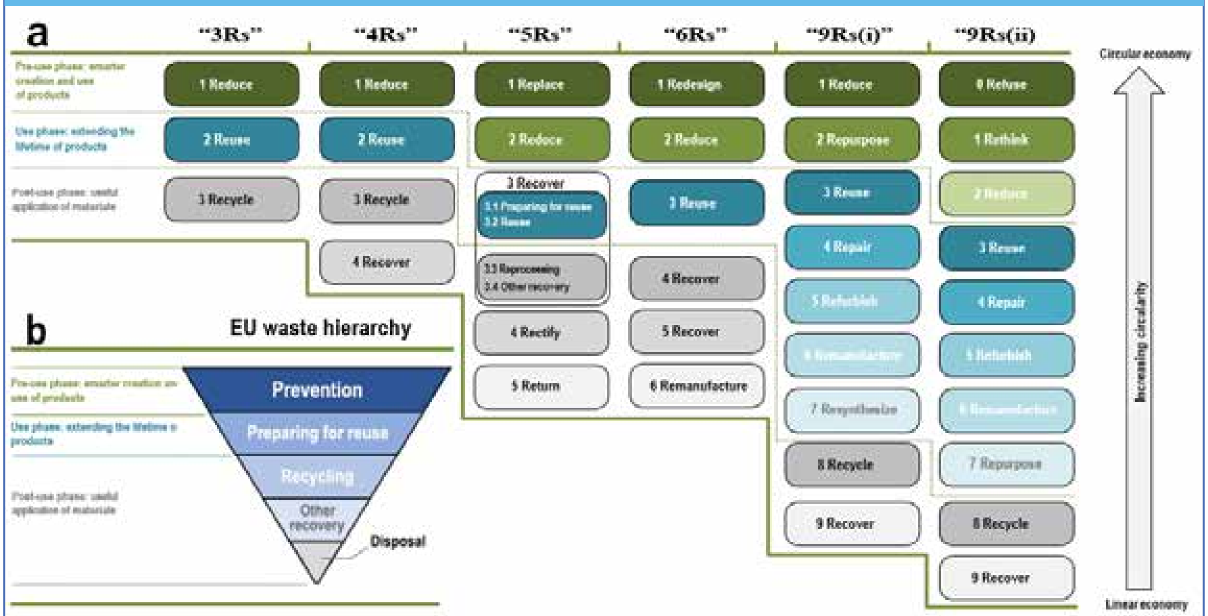
Member States (Council Directive 75/442/EEC, 1975). Europe's WFD includes new standards for waste prevention and established terms like "prevention", "recovery", and "end-of-waste criteria" that are important to waste management globally. These new standards place a strong emphasis on the need to reduce waste while also prioritizing the protection of environmental and human health (Figure 19b, c, d). The waste hierarchy has been refined further over time, as reflected in Figure 19.

However, the waste hierarchy is typically limited by mostly only considering environmental factors around waste management, and not also considering logistical, social or economic factors, or the need to encourage a shift towards circularity. Simon (2019) argues that a new "Zero Waste" hierarchy is necessary to shift the focus from waste management to resource management, given the new conceptual framework provided by the circular economy model. With this, the aim should be to move towards a system that preserves material value and ultimately eliminates waste (Figure 19h). The Zero Waste hierarchy further argues that non-stabilized waste disposal, littering, and any type of combustion or co-combustion of mixed waste, with or without oxygen, are all practices that need to be discontinued since they divert resources away from the hierarchy's higher priority levels (Simon, 2019).

The 3Rs (reduce, reuse and recycle) is another key circular economy concept that is closely related to waste management principles (Ghisellini *et al.*, 2016). Like the evolution of the waste hierarchy (Figure 19), Figure 20 shows the nine additional Rs that have been added to this rule/framework over time (Gharfalkar *et al.*, 2015; Kirchherr *et al.*, 2017; Potting *et al.*, 2017; Sihvonen and Ritola, 2015; Yan and Feng, 2014). A 2021 FAO report employed a 6R model that included refuse (i.e. avoid using plastics), redesign, reduce, reuse, recycle and recover to assess the use of plastics in the agricultural sector, including plastics in fishing gear and fishing gear recycling (FAO, 2021).

The waste hierarchy and the R-based circular economy concepts are closely connected (Figure 20). These concepts consider the whole life cycle of a product, including the pre-use, use, and post-use phases, from a life-cycle perspective. They

FIGURE 20. COMPARISON OF R-BASED CIRCULAR ECONOMY CONCEPTS (A) AND THE WASTE HIERARCHY FRAMEWORK (B)



Notes: Information based on 3Rs (Ghisellini *et al.*, 2016); 4Rs (Kirchherr *et al.*, 2017); 5Rs (Gharfalkar *et al.*, 2015); 6Rs (Yan and Feng, 2014); 9Rs(i) (Sihvonen and Ritola, 2015); 9Rs(ii) (Potting *et al.*, 2017).

Source: Modified and adapted from Zhang *et al.* (2022). An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. Science of The Total Environment, 803, 149892 (https://doi.org/10.1016/j.scitotenv.2021.149892).

have been developed through time to emphasize the design and use of a product before it becomes waste. The waste hierarchy, R-based concepts and circular economy model more broadly all share aims to manage waste via rethinking, redesigning, and reusing in order to increase a product's resource effectiveness and decrease the formation and negative effects of waste. These models and concepts have important applications to the improved circularity and stewardship for fishing gears, as discussed in Sections 1.4.3 and 1.4.4.

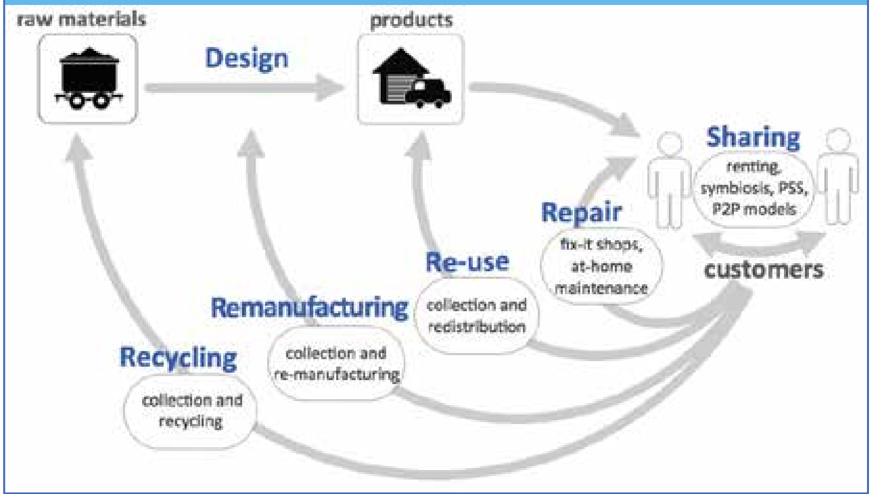
1.4.3 Design strategies to improve product circularity of fishing gear

As circular economy (CE) principles become more significant policy drivers, implementing systems to increase the lifetime and value of fishing gear, components, materials, and accessories in economic and social systems will become more crucial. Longer gear lifetimes can be counterproductive, however, if they result in higher risks for gear damage and ALDFG, or the release of microplastics. The life cycle and "eco-design" principles are therefore important in fishing gear design to ensure maximized gear lifetimes and end-of-life gear value for reuse or recycling, while minimizing waste and pollution. However, considerations relating to product life-cycle principles (discussed in Section 1.4.1) and "eco-designs" are relatively new ideas in the fishing gear industry (Charter *et al.*, 2020). This section summarizes an array of design strategies that can support improved fishing gear circularity in the earliest stages of the waste hierarchy and circular economy models. In order to enhance and optimize the sustainable design process, interaction between fishing gear producers/manufacturers and operators/users is essential (Charter *et al.*, 2020).

Harmonized standards for the circular design of fishing gears are also important to ensure that gears are made to appropriate quality standards that support reuse, repurposing and recyclability at the end of a gear's life. For example, the European Commission (EC) has started to develop criteria for circular fishing gear design, as per Article 8(9) of Directive (EU) 2019/904 (2019). These criteria should be aligned and developed in collaboration with existing industry and governmental standardization bodies, such as the European Committee for Standardization (CEN) in the case of Europe.

From a life-cycle perspective, the use phase is crucial to extending the lifetime of fishing gear, with fishing operators and fishers already repairing and modifying fishing gear to a large extent. Fishing gear designs that support "product life extension" to allow for "multiple lives" of fishing gears when in use are important first steps to improving their overall circularity. Consideration should also be given to the maximum working lifetime of gears, to ensure that gears and their components are responsibly returned at the end of their life, before they become too degraded and at risk of further damage or loss in the marine environment. Gear design that includes information around anticipated gear and component lifetimes, including the date of manufacture and recommended repair and replacement schedules, could assist fishers and regulators to undertake regular gear repairs and replacement during the use phase. Figure 21 shows a variety of options for extending the lifespan of fishing gear before recycling at the end of its life.

FIGURE 21. FUNCTIONAL PILLARS OF A CIRCULAR ECONOMY



Notes: PSS means Product-Service System business model, and P2P means Peer-to-Peer lending (discussed in Table 6).

Source: EIO and CfSD (2016). Eco-innovate! A guide to eco-innovation for SMEs and business coaches. Eco-Innovation Observatory, funded by the European Commission, DG Environment, Brussels.

The number of different materials and polymer types used in the current design, development, manufacture, and/or assembly of fishing gear present serious challenges for fishing gear recycling at the end-of-life stage (as discussed in Section 1.2). When reuse and repurposing possibilities are no longer practical, simplifying and clearly identifying the types and quantities of materials and polymers used in fishing gear will permit more effective recycling. Section 1.3.1 discusses specific fishing gear design considerations to increase the recyclability of fishing gears. In addition, the ability to disassemble the components and thus separate the materials should also be considered at the design stage (Bertling and Nühlen, 2019).

Design for fishing gear circularity can be considered for the entire gear life cycle, including for the sourcing of materials, manufacture/assembly, transport and distribution, use and end of life. A variety of eco-design strategies at different product development and life-cycle phases, to enhance product circularity, are highlighted in Table 4. While the checklist in Table 4 was not created specifically for fishing gears, many of the design considerations can apply to fishing gear, including for better circularity and recyclability.

Education and training programmes, as well as raising public awareness of the economic and environmental implications of circular fishing gear design are essential to supporting and advancing efforts to improve the circularity of fishing gears. Concurrently, regional and national collection, sorting, reuse, and recycling systems must be designed and developed to ensure appropriate infrastructure and logistics for the management of unwanted fishing gear.

TABLE 4. INDICATIVE ECO-DESIGN CHECKLIST THAT MIGHT BE APPLIED TO THE DESIGN AND DEVELOPMENT OF FISHING GEAR

Design focus area	Options for design improvement
Design for sourcing of materials	Reduce the product's size and weight
	Increase the use of recycled materials to replace original materials
	Use more renewable resources
	Increase the use of recycled components
	Remove dangerous substances
	Utilize components that have less embodied energy and/or water
Design for manufacture/assembly	Reduce energy use
	Minimize process waste
	Use internal resources or recycled materials from process waste
	During production, minimize emissions to the air, water, and soil
Design for transport and distribution	Reduce product dimensions and weight
	Achieve the best form and volume for the maximum package density
	Optimize distribution in terms of fuel consumption and emissions
	Optimize packaging to meet legal requirements
	Increase the amount of recycled materials used in packaging
	Remove dangerous elements from packaging
Design for use (including installation, maintenance and repair)	Increase the availability of replacement components
	Maximize maintenance efficiency
	Optimize practicality of disassembly and reuse
	Avoid design elements that limit reuse
	Use less energy during disassembly
	Reduce emissions to the earth, water, and air
Design for end-of-life	Improve the energy efficiency in the recycling of materials
	Avoid design elements that inhibit material recycling
	Reduce the quantity of waste produced after reuse and recycling

Source: Modified and adapted from Charter *et al.* (2020). Creating business opportunities from waste fishing nets. Opportunities for circular business models and circular design related to fishing gear. Blue Circular Economy (BCE) Final Report.

1.4.4 Circular business models (CBMs) for fishing gear

Fishing gear design and development often occurs as an informal process based on the personal and professional experiences of fishers, manufacturers, producers and assemblers, rather than formalized design and development processes typically seen in other market sectors. This means that circular designs are often not considered or prioritized (Charter *et al.*, 2020). So far, only a relatively small number of commercial products have been made from upcycling, repurposing and recycling unwanted fishing gears worldwide. Case studies and examples are provided in Part Two (Practical examples of fishing gear recycling practices). The development of circular business models (CBMs) for fishing gears can help to raise awareness and incorporate product life-cycle principles into the work of fishing gear manufacturers, assemblers and producers, and thus contribute to the development of a circular economy (CE) around fishing gear.

Circular business models can be supported by ports, coastal cities, towns and fishing communities, through the launching of initiatives that support small and medium-sized businesses in the recycling, upcycling and repurposing of unwanted fishing gear (Charter *et al.*, 2020). Public–private partnerships can also support the larger-scale repair, service, remanufacturing and recycling of fishing gear, as well as the development of appropriately sited waste collection (Charter *et al.*, 2020). The size and scale of the business and associated fishing operations will determine the CBM, as operators strive to maintain a sufficient-enough quantity of material flow that meets the operators' time and material quality requirements. For example, fishing gear repair and reconditioning are relatively common with small-scale operators, while larger operators typically employ external repair and refurbishing services.

Critical factors for fishing gear recycling CBMs identified by stakeholders include: the availability of *sufficient raw material*; a functioning *supply chain* for EOLFG and recovered ALDFG collection, segregation and transport to recycling facilities; available, feasible and sustainable *recycling technology*; *ease of recycling* (e.g. materials are not too mixed or too contaminated for the pre-processing requirements); *policy drivers* to support fishing gear recycling processes; stakeholder *awareness*, including for the post-collection treatment of EOLFG and recovered ALDFG; and a *market economy* including market demand for, and acceptance of, products made from recycled fishing gears (Deshpande *et al.*, 2020a).

Table 5 and Table 6 outline strategies to support CBMs. They are included in full in this report as they provide a comprehensive examination of how CBMs support sound unwanted fishing gear management, including the potential for fishing gear recycling. The technical measures and policy instruments summarized in Section 1.3, including regulatory interventions, market-based instruments and EPR schemes can also support and drive opportunities for CBMs. Table 5 highlights current CBM practices, as well as prospective new possibilities that could become more pertinent in the light of recent developments and legislative modifications. Table 6 lists further potential advantages and threats for future CBMs: it considers the stakeholders who own and use the business models, the opportunities the models offer, and the threats that might prevent the models from being adopted.

TABLE 5. EXISTING CIRCULAR BUSINESS MODELS (CBMS) AND ADDITIONAL OPPORTUNITIES

Circular economy business model	Existing practices	Additional opportunities
Produce as needed (made to order and custom-made)		
Creating a product or offering a service only when a consumer need has been identified and verified.	Depending on the demands of the particular fisher and their fishing techniques, fishing gear is frequently custom-made.	• New digital manufacturing technologies (the integrated application of digital/computer technologies to manufacturing) have the potential to increase customization while reducing production costs and times. • Use eco-design techniques to cut down on resource usage throughout the life of a product. • Combine with other CBMs to increase revenues. Examples include product service systems, reuse, market brokerage, and remanufacturing and reconditioning.
Extension of product life		
Brand-new items designed with extended lifespans (durability).	Producers supply fishing operators with a fishing net plan and patch materials. Long-lasting materials are more widely used, lengthening the life of fishing gear.	• Combine with other CBMs to increase revenues. Examples include services for refurbishment, repair, remanufacturing, and reconditioning. • Combine with eco-design techniques and modular design to promote high-quality and financially viable reuse. • Use eco-design strategies to cut down on resource usage throughout the life of a product.
Encouraged reuse		
Reuse whether or not repairing or upgrading (supplied, either free of charge or resold).	Many fishing gear parts, such as weights and buoys, are regularly reused by producers and operators.	• Given the customized nature of fishing gear systems, reuse is quite rare. However, there is opportunity for more reuse of key fishing gear parts. Producers, centralized/localized market brokerage and storage, fishing operators may all take on the task of commercializing reusable parts. • Combining CBMs to create new revenue streams. Examples include refurbishing, repairing, remanufacturing, and reconditioning as well as recycling, upcycling, and downcycling. • Combine with other CBMs (such as product life extension and modular design) and eco-design techniques to promote high-quality and commercially sustainable reuse.
Product Modular Design		
Products designed to allow the individual components to be updated.	Key components of fishing gear can be made to be easily removed, disassembled and replaced.	• Combine with other CBMs to increase revenues. For instance, repairing, remanufacturing, and reconditioning. • Work in conjunction with other CBMs (such as product life extension) and eco-design approaches to promote high-quality and economically sustainable reuse. • Key gear components whose failure could lead to ALDFG can include requirements for maintenance and replacement communicated by the producer to the purchaser (fisher). Anticipated maintenance schedules and maximum working life can be specified by the producer.

Source: Modified and adapted from Charter *et al*. (2020). Creating business opportunities from waste fishing nets. Opportunities for circular business models and circular design related to fishing gear. Blue Circular Economy (BCE) Final Report.

TABLE 6. OPPORTUNITIES AND THREATS FOR NEW CIRCULAR BUSINESS MODELS (CBM)

Business model	Opportunities	Threats
Incentivized return		
Incentivize customers to return used or unwanted products to the manufacturer. The producer either remanufactures the product or recycles the raw components. Benefits are frequently given in the form of a discount on a new product in consideration for the return of an obsolete one.	• Allow manufacturers to comply with forthcoming SUP and PRF directives without additional EPR costs; • producers may potentially receive more orders if paired with take-back discounts or a deposit programme; • possible increase of fishing gear collection, lowering unlawful disposal at sea; and • if reuse and recycling are combined, there is a greater chance that gear will enter circular resource flows.	• Producers could have to pay more owing to increased logistical needs, sales discounts, or labour and storage requirements to process used gear returns; and • producers need more resources to conduct diagnostics to determine retainable value in order to guarantee that fishing gear enters cyclical resource flows.
Lease agreement		

Not selling ownership of a good or service, but rather leasing access to it. This can be done on a business-to-business (B2B) or business-to-consumer (B2C) basis. Because the lease retains ownership of the asset and may be paired with service- or performance-based business models, in the context of a circular economy an "operating lease" model is generally likely to work best for product service system models. When depreciation, maintenance, and disposal/replacement expenses are taken into consideration, the lessee's capital expenditure is often less than an outright purchase. During the lease time, the lease often has better overall profitability and keeps ownership.	• Provide fishing operators with access to reliable, high-quality fishing gear for a reduced upfront investment and, if depreciation, maintenance, and disposal/replacement expenses are taken into consideration, at a lower lifetime cost. Fishing operators will also have proper fishing gear ready for usage, since they lease fishing gear from the producers and pay a regular cost for their use, maintenance, and replacement to be guaranteed.
	• Allow producers / manufacturers to maintain ownership of fishing gears, enabling them to:
	  • comply with the SUP directive, making sure fishing gear is returned when it is no longer needed;
	  • increase the resilience of their fishing gear by developing real-world failure mode and effects analysis (FMEA);
	  • implement multiple life strategies for fishing gear through product life-extension, modular design, reuse, repair, refurbishment, and remanufacturing to increase profit from individual fishing gear; and
	  • generate additional revenue by offering used fishing gear to recyclers.
		• Demands resources (capital costs) to convert producer accounting (upfront sales profits) and sales (bonuses) procedures from one-off sales to leasing;
		• grants, accounting (depreciation), and cash flows of fishing operators may impede monthly payments;
		• legal clarity on responsibility and liability issues between producers and fishing operators on maintenance, repair, handling, training, etc. necessary for service contracts;
		• producers assume responsibility for uncontrollable damages, entanglements, misuses, and other situations that can reduce profits; and
		• a limited uptake may be caused by the culture and feeling of control via ownership among fishing operators.

Performance-based (pay for success)		

Instead of providing the product or service itself, companies offer product performance or defined results. Consumers purchase a certain level of performance, and the company's main income source is the fulfilment of demand through payments for performance provided. The running business continues to own the property.	• Enables fishing operators to cut costs if they have low catch performance while paying for key fishing gear productivity –catch performance (by volume, quality, etc.). Especially when depreciation, maintenance, and disposal/replacement costs are taken into consideration, it may lead to a reduced capital investment and perhaps lower lifetime costs.
	• Enables producers to keep possession of fishing gear, allowing them to:
	  • ensure fishing gear are returned at end-of-life to meet SUPD requirements;
	  • perform real-world FMEA (Failure Modes and Effects Analysis) for a more durable fishing gear;
	  • utilize multiple life strategies for fishing gear, such as product life-extension, modular design, reuse, repair, refurbishment, and remanufacturing, to increase profit from individual components of fishing gear; and
	  • market used fishing gear to recyclers to get additional revenue.
		• Requires resources (capital investment) to transition producer accounting (upfront sales profit) and sales (bonuses) practises from one-off sales to performance-based compensation;
		• producers assume responsibility for catch productivity, which is based on a number of factors they have almost no control over, such as fishing operator expertise or depleting fish supplies;
		• unreliable catch productivity would lead to unreliable cash flow and decreased producer profit;
		• legal clarity on duty and liability issues between fishing gear manufacturers and fishing operators on maintenance, repair, handling, training, etc. necessary for service contracts;
		• producers assume responsibility for uncontrollable damages, entanglements, misuses, and other situations that can reduce profits;
		• a limited uptake may be caused by the culture and perception of control via ownership among fishing operators; and
		• market price volatility, as well as a lack of transparency in the quantity and value of catch, makes it difficult for producers and fishing operators to determine cost models and agree on reasonable rates for performance.

Sharing platforms/resources		
Shared access or "collaborative consumption" between users, groups, or organizations, but only when some sort of transactional agreement (which could be paid) is offered. Increase the rate at which goods and services are used by allowing customer ownership and shared usage. Allowing users to access a product and utilize it as required, rather than buying it entirely.	• Enables small-scale fishers to generate additional revenue by renting out their infrequent, underutilized, or port-based fishing gear; • helps start-up or small-scale fishing companies reduce expenses by eliminating the need for capital investments in the form of paying per use for irregularly used or port-based fishing gear; • possibility for a digital platform to make income (based on a percentage of rental rates) by acting as an intermediary between parties and lowering the risks faced by fishing operators; and • possibility for a community cooperative to lend local fishers port-based fishing gear or equipment for end-of-life treatments.	• Demands an open, cooperative, and highly trustworthy industry culture, which might be difficult in the extremely competitive commercial fishing sector; • requires legal clarity on who is responsible for improper usage, maintenance, and damage; and • if fishing gear is needed at the same time, such as in small ports where fishing is dependent on the tides, difficulties may develop.

Peer-to-Peer (P2P) lending			
The majority of peer-to-peer lending of products happens between members of the public or businesses, although neither party engages in a direct financial transaction nor secures an income. More socially driven than commercially, where access might improve local ties. Business advantages for B2B financing might include lower costs compared to acquiring the relevant goods/services directly.		• Allows manufacturers of fishing gear to reduce expenses by switching out virgin raw materials for recycled ones, especially if the manufacturer keeps ownership of the fishing gear through the use of lease agreements, performance-based compensation, and return incentives; • sales of second-hand fishing gear provide fishing operators with a new source of income; and • possibility to launch a business collecting or recycling outdated fishing gear.	• Demands an open, cooperative, and highly trustworthy industry culture, which may be difficult in the highly competitive commercial fishing sector; • requires legal clarity on who is responsible for improper usage, maintenance, and damage; and • if fishing gear is needed at the same time, such as in small ports where fishing is dependent on the tides, difficulties may develop.
Refurbish, repair, remanufacture and recondition			
After remanufacturing, a product is given a second life by the process of restoring its functionality to "like-new" condition, which is made easier by the device's design for disassembly. Enables the fishing gear manufacturer to resell the items and get a second or subsequent payment from a new customer.	Refurbish: making something appear like new but just slightly enhancing its usefulness is an example of the aesthetic enhancement of a product, component, or material.	• Possibility for cooperatives or social enterprises to provide port-based cleaning services; and • allows fishers to spend less money replacing their gear.	• A lack of consumer demand may limit the ability to recover operational costs; • need a rapid turnaround to coincide with the downtime of the fishing operator; and • if only the aesthetics of a fishing gear are improved, but the gear is still used and/or damaged, a fisher may be encouraged to use this gear beyond its safe working life, which could result in ALDFG.
	Repair: restoring a defective or damaged product, component, or material to a useable condition.	• While the majority of fishing operators repair their fishing gear themselves, and some fishing gear producers offer repair services that are either port-based or at their facilities, this is an opportunity for a more coordinated approach to repair in the industry; and • opportunity for co-operatives or social enterprises to offer port-based repair services.	• Labour-intensive work could make repair and reconditioning costs unviable; • need a rapid turnaround to coincide with the downtime of the fishing operator; and • a fishing gear may still contain degraded or worn components following repair, which can cause risks for abandonment, loss or discard.
	Recondition: bringing a used product back to full functionality by upgrading or fixing critical parts that are close to failure.	• Possibility for cooperatives or social enterprises to offer port-based reconditioning services.	-
	Remanufacture: restore a used item to at least its original functionality while providing a guarantee that it is equivalent to or better than a brand-new product.	• Possibility for cooperatives or social enterprises to provide centralized or port-based remanufacturing services; • possibility for manufacturers to generate new sources of revenue if integrated with other circular business models including product life-extension, modular design, leasing agreements, performance-based compensation, and incentive-based return; and • enables fishing operators to reduce spending using less expensive fishing gear.	• Resource-intensive tasks such as inspection, storage, disassembly, component repair and replacement, testing may increase prices over the cost of new fishing gear; • affected by material deterioration, particularly with regard to plastic components; and • low and irregular rates of collection of used fishing gear may lead to an unreliable supply chain.

Source: Modified and adapted from Charter *et al*. (2020). Creating business opportunities from waste fishing nets. Opportunities for circular business models and circular design related to fishing gear. Blue Circular Economy (BCE) Final Report.

Part II – Practical examples of fishing gear recycling

2. Practical examples of fishing gear recycling

Part Two shares practical examples of fishing gear recycling initiatives around the world that have the potential to be applied more widely, from local to national and regional scales. Examples are provided for unwanted fishing gear repurposing and recycling, including mechanical and chemical recycling and energy recovery initiatives. Innovative products made from recycled fishing gears are highlighted to showcase the diversity of goods that might be created from unwanted fishing gear recycling. Part Two ends with an example of a regional initiative to support the circular economy for fishing gears, including supporting the development of circular business models for fishing gear recycling. Most of the examples provided apply to unwanted commercial fishing net recycling, as this is generally the most common type of gear currently being recycled globally.

For additional examples of fishing gear recycling beyond this report, the 2022 publication *Products from Waste Fishing Nets: Accessories, clothing, footwear, home ware and recreation* is another excellent resource for examples of products made from unwanted fishing nets (Charter and Carruthers, 2022). The *GloLitter Report on good practices to prevent and reduce marine plastic litter from fishing activities* (Giskes *et al.*, 2022) is another helpful resource for examples of solution projects to prevent, mitigate and remediate ALDFG. Examples of relevant fishing gear recycling initiatives highlighted in that report, which are not included here to avoid the duplication of information, include Coast 4C (formerly Net-Works™) (the Philippines), Net Positiva (Argentina, Chile, Peru and the United States of America) and Fishing Net Gains Project (Nigeria). The report *Effective Ghost Gear Solutions: Learning from what works* also provides some practical examples of fishing gear recycling and upcycling initiatives (Drinkwin, 2020).

2.1 RECOVERY AND COLLECTION OF FISHING GEAR FOR RECYCLING

Section 2.1 presents practical examples of initiatives focused on the recovery and collection of fishing gear for recycling. These include examples from small-scale, artisanal fisheries to national and regional initiatives. An example of recreational fishing gear collection is also presented, as well as an example of a market-based incentive to support the recovery and return of unwanted fishing gear. These examples are shared to show the diversity of initiatives available globally to support the collection of unwanted fishing gears and the subsequent preparation for recycling across different geographic scales and types of fisheries.

2.1.1 Small-scale, artisanal fishing gear collection for recycling: *Net-works Cameroon*

The Net-works Cameroon project is included as an example of fishing gear collection for recycling in small-scale artisanal fishing communities, one which supports local communities, marine habitats, and livelihoods. *Net-works*, a collaboration between the Zoological Society of London (ZSL) and Interface Inc., extended its work to the Douala-Edea area of Cameroon, Central Africa, in mid-2015, after a successful start in the Philippines.[20] The Darwin Initiative supported the pilot project at the Lake Ossa

[20] See the case study on Coast 4C (formerly Net-Works™) (Philippines), presented in the Report on good practices to prevent and reduce marine plastic litter from fishing activities (Giskes *et al.*, 2022).

Wildlife Reserve. More than 80 percent of the families in the Lake Ossa region rely primarily on the lake for their survival. Discarded fishing nets entangle manatees and other animals, ruining natural habitats and posing a major threat to the lake's ecology.

Net-Works has worked closely with local communities to organize **a fishing net collection hub, build the machines required to compress and prepare the nets for recycling, and establish local community banks**, which are central to the Net-Works model (Langenheim, 2019). At the time of this report, over 2 400 kg of unwanted fishing nets have been collected for recycling since the start of the project. The collected nets are shipped to Europe where they are transformed into yarns that can be used for clothing products, such as Prada's line of Re-Nylon products (Langenheim, 2019). Because the volume of nets in Cameroon's coastal areas is much higher than in Lake Ossa, Net-Works plans to extend this model to Cameroon's coastal communities to ensure an even larger and more consistent source of used fishing nets enter the recycling supply chain.

2.1.2 National-level fishing gear collection for recycling: Sweden - Swedish Agency for Marine and Water Management and Sotenäs Centre of Symbiosis (Sotenäs Symbioscentrum)

A variety of agencies who work collaboratively to recover, collect and recycle fishing gears are active in Sweden, notably the Swedish Agency for Marine and Water Management (SwAM) and the Sotenäs Centre of Symbiosis. Sweden's efforts to manage unwanted fishing gear responsibly – including through the mandatory reporting of lost gear, as well as the **recovery and collection of unwanted gears for recycling, and support for fishing gear responsibility schemes** – are included in this report as an example of **national-level efforts that support fishing gear recycling**.

The SwAM coordinates a variety of programmes designed to minimize the occurrence of ALDFG and responsibly collect and return recovered ALDFG and EOLFG to port for recycling. This includes obligations to report lost fishing gear within 24 hours of the loss under Regulation (EC) 1224/2009 (2009), as well as supporting ALDFG detection and clean-up through the Ghostguard tool and ALDFG education and awareness-raising projects with recreational and professional fishers (Axelsson, 2021). Since 2017, many ALDFG clean-up initiatives in Sweden have been carried out by fishers and expert divers with support from the European Maritime and Fisheries Fund (Axelsson, 2021).

The Sotenäs Centre of Symbiosis (*Symbioscentrum*) also supports unwanted fishing gear collection and recycling efforts, in collaboration with *Fiskareföreningen Norden* (also known as the Nordic Fishermen's Association) (Charter and Whitehead, 2022). The *Symbioscentrum* is an industrial and social symbiosis department that was founded by *Sotenäs* Municipality in 2015 to apply industrial symbiosis (waste = "food") principles to strengthen the local community socially, economically and environmentally. The Sotenäs Marine Recycling Centre (SMRC) is Sweden's only recycling centre for fishing gear and focuses on collecting and processing marine plastic litter, including ALDFG. The latter includes fishing gears such as nets, cages and lobster pots. The SMRC is developing examples of best practice related to the recycling of fishing gear that includes collection, sorting and circular design (Charter and Whitehead, 2022). The goal is to share knowledge and experience related to test methodologies (the testing of different types of polymers for use in the manufacture of new products); technology methodologies (manufacturing methodologies); and share information on how to set up and manage a fishing gear recycling system with interested parties.

Sweden's SPIRAL project collaborates between SwAM, Municipality of Sotenäs, the Swedish Environmental Protection Agency and the Swedish Board of Agriculture to support the introduction of a fishing gear producer responsibility scheme. The fishing gear producer responsibility scheme is being developed through active dialogue and information sharing with fishing gear producers; it also includes testing around the collection and recovery of waste fishing gear (Swedish Agency for Marine and Water Management, 2022). More information around Sweden's fishing gear responsibility scheme can be found on Swedish Environmental Protection Agency (2023).

2.1.3 Regional fishing gear collection for recycling: Redes de América

Redes de América is the fishing net and gear recycling programme of the Latin American Alliance for Sustainable Fishing and Food Security (ALPESCAS), which brings together 11 countries in the region.[21] This private law organization has a Circular Economy Committee, which has generated collaboration agreements through the Redes de América programme with fishing chambers from Argentina, Ecuador, Chile, Costa Rica, Mexico, Panama, Peru, and Uruguay. This programme seeks to generate synergy in their objective to use unwanted fishing and aquaculture nets and gear to generate circularity for their materials. The recycling of fishing and aquaculture nets and gear has been extended to the collaborating countries using a bridge model between fishing chambers, their partner companies and companies specializing in plastic recycling. Together these companies – Bureo (Net Positiva) and Comberplast (Atando Cabos) – recycled more than 7 000 tonnes of decommissioned fishing nets between 2018 and 2022. This preventive strategy for marine pollution is oriented towards the generation of sports, textile, industrial and high-fashion products, and has been successful in generating interest from fishing companies to give their fishing and aquaculture gear an appropriate end-of-life use. Part of the economic returns from the recycled products are returned to fishing communities, which are located in the donating fishing companies' area of influence.

Redes de América is currently developing a certification system that will address the mass balance of new fishing and aquaculture nets and gear acquired by companies. The system will certify that the end-of-life destination is recycling and not landfills or loss in the environment. Certification is projected to be given to companies that can demonstrate they recycle at least 50 percent of their total fishing gear, and will reach 90 percent within a couple of years as the certification is tested and developed. The procedure incorporates strict accounting and physical monitoring. It is expected that this certification will be able to provide information to consumers regarding fishing companies' compliance with the traceability of their nets and fishing gear. The information will extend from purchase to the end of their useful life and their disposal in formal circular recycling systems for the generation of low-impact products. This mass balance certification is operational as of 2023.

2.1.4 Regional fishing gear collection for recycling: *Fishing for Litter*

The Fishing for Litter (FFL) programme (https://fishingforlitter.org) is included to provide an example of unwanted fishing gear recovery for disposal, including recycling, at a regional (European) level. The FFL scheme is a relatively simple yet innovative approach to reduce and recover marine litter, including ALDFG, introduced by *Kommunernes International Miljøorganisation* (Local Authorities International Environmental Organization) (i.e. KIMO International) in 2002. KIMO is a network of local governments that represents over 80 member municipalities in 9 countries.[22]

[21] Argentina, Chile, Colombia, Brazil, Costa Rica, Ecuador, El Salvador, Mexico, Panama, Peru, and Uruguay.

[22] Belgium, Denmark, Germany, Ireland, Lithuania, the Kingdom of the Netherlands, Norway, Sweden, and the United Kingdom.

FIGURE 22. FISHERS INVOLVED IN THE FISHING FOR LITTER PROJECT

© KIMO

Notes: Free bags are provided to fishers to collect the marine litter, including ALDFG items, caught during fishing operations.

These municipalities are working together for healthy seas, clean beaches, and thriving coastal communities in the North-East Atlantic and Baltic regions. Interest has been expressed to replicate and adapt aspects of this programme in Africa, Asia and the Americas.

While it began as a grass-roots initiative, in 2014 FFL was included in the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)'s regional action plan as a voluntary measure for contracting parties. In 2019, it was incorporated in the European Union's Port Reception Facilities Directive (EU) 2019/883 (2019), where the collection of "passively fished waste" is defined as "waste collected in nets during fishing operations" (Mannaart and Bentley, 2022).

The scheme provides fishing vessels with large and durable bags (Figure 22) that they can use to collect whatever marine litter items, including ALDFG, that they "catch" while fishing. Fisher participation is voluntary, and no additional action is needed other than collecting the litter encountered during fishing and returning it to port in the bags provided. The ports and associated waste collectors store, transport and process the waste returned (Mannaart and Bentley, 2022). The FFL scheme pays for the litter collection and disposal, including recycling, demonstrating the fishing industry's commitment to environmental protection. It is crucial for the success of FFL initiatives that there should be no extra disposal costs for the participating fisheries, in order to incentivize delivery of all collected litter to shore. The FFL initiative offers a means of removing marine litter from the sea and seabed and promotes environmental awareness among fishers, the fishing industry, and the public. While dedicated ALDFG cleaning operations are not carried out under the FFL scheme, lost net fragments and other ALDFG and litter items from the fishing sector are collected. The two types of cleaning actions are therefore complementary. One example of the programme's effectiveness can be seen in the amounts of marine litter collected, including ALDFG. More than 1 844 tonnes of marine litter were collected in Scotland from 2004 until 2022, with 4 189 tonnes collected in the Kingdom of the Netherlands from 2011 to 2021 (Mannaart and Bentley, 2022).

FIGURE 23. MONOFILAMENT RECYCLING BIN INSTALLED IN CALIFORNIA THROUGH THE "REEL IN AND RECYCLE" PROGRAMME

Notes: the "Reel In and Recycle" programme was launched by the BoatUS Foundation with grant funding from the National Fish and Wildlife Foundation and the NOAA Marine Debris programme.

Source: Modified and adapted from Morishige (2010). Marine Debris Prevention Projects and Activities in the Republic of Korea and United States: A compilation of project summary reports. NOAA Technical Memorandum (NOS-OR&R-36).

2.1.5 Recreational fishing gear collection: Reel In and Recycle program (BoatUS Foundation)

Most examples of unwanted fishing gear recovery and collection apply to commercial fishing gears, because of the large volumes of these gears that can be made available for recycling. The *Reel In and Recycle* program in the United States is presented as an example of an unwanted **recreational fishing gear collection and recycling initiative**.

With grant assistance from the United States' National Fish and Wildlife Foundation and the NOAA Marine Debris Program, the BoatUS Foundation started the Reel In and Recycle Program in 2006 (Morishige, 2010). The programme's goal is to establish a state-wide network of fishing line recycling bins (Figure 23) to assist mostly recreational fishers to properly dispose of used fishing lines (Morishige, 2010). Individuals can choose to either obtain a free bin or build their own through the programme. The BoatUS Foundation also provides a video podcast (Morishige, 2010) with step-by-step instructions for those groups interested in building their own used fishing line collection bins. See further information at http://www.boatus.com/foundation/Monofilament/build.asp.

2.1.6 Market-based instrument (MBI) example for unwanted fishing gear recovery and collection: *Marine debris buy-back programme in the Republic of Korea*

Section 1.3.5 of this report discusses the opportunities to use market-based instruments (MBIs) to support the recovery and collection of unwanted fishing gear for the purposes of recycling, including for unwanted fishing gear "buy-back" programmes or reward schemes. The Republic of Korea's marine debris buy-back programme provides an example of such an MBI for marine debris more broadly, which includes the collection and return of unwanted fishing gears.

The marine debris buy-back programme's specific objectives are: (i) replace expanded polystyrene (i.e. *Styrofoam*) fishing buoys with eco-friendly buoys to reduce marine litter; (ii) prevent ghost fishing and conserve marine ecosystems by using degradable fishing gears; (iii) remove lost and submerged fishing gears to preserve marine eco-systems and prevent ghost fishing; (iv) support financial incentives for fishers to return unwanted fishing gear to port; (v) build a basic infrastructure for efficient marine litter collection; and (vi) charge a deposit when purchasing fishing gears, and subsequently refund their return as EOLFG (Morishige (2010). Objective (vi) is also a specific example of a deposit-return MBI.

The Ministry of Land, Transport, and Maritime Affairs of the Republic of Korea supported the establishment of a voluntary programme of floating receptacles where marine wastes, including unwanted fishing gears, can be deposited as part of this programme. Morishige (2010) determined that this programme resulted in a 30 percent reduction of marine litter.

2.2 REPURPOSING UNWANTED FISHING GEAR: "GOOD NET" VOLLEYBALL NETS AND THE "GHOST LEASH"

Under the circular economy and waste hierarchy frameworks discussed in Section 1.4, repurposing unwanted fishing gears is preferred over recycling as it helps to prolong the life cycle of the gears without changing or downcycling their material composition. Repurposing recovered ALDFG can be a good alternative to the generally more resource-intensive recycling methods outlined in Section 1.2, especially if the recovered gears are complicated to recycle because of contamination or mixed polymers.

A relatively simple example of repurposing recovered ALDFG is provided by the collaboration between the International Volleyball Federation (FIVB) and the Ghost Fishing Foundation, a marine conservation organization. These organizations came together to repurpose recovered ALD fishing nets into volleyball nets for use by local coastal communities around the world (FIVB, 2019). An example of these repurposed nets is shown in Figure 24. The first athletic event to use recycled nets was held on Brazil's famed Copacabana beach, which also hosted the beach volleyball competition at the 2016 Rio Olympic Games (FIVB, 2019). This was the first of a series of FIVB-endorsed volleyball matches using ALD fishing nets as volleyball nets. Matches are set to take place in various locations around the world to raise awareness about the harm that ALDFG causes to marine life and environments.

FIGURE 24. LOCAL CHILDREN PLAYING BEACH VOLLEYBALL USING NETS FROM RECOVERED ALDFG

Source: Modified and adapted from FIVB (2019). Good Net Volleyball Sustainability Project Launched on Copacabana Beach. 16 March 2019. News - Good Net Volleyball Sustainability Project launched on Copacabana Beach (www.fivb.com).

FIGURE 25. CROSS SECTION OF THE GHOST LEASH. EACH LEASH IS MADE FROM 81.5 M^2 OF TWISTED GHOST NET AND WRAPPED IN WASTE FABRIC AND WASTE THREAD. THE GHOST LEASH IS 1.5 M LONG AND WEIGHS 275 GRAMS

Source: Modified and adapted from Olive Ridley Project (2023). Ghost Leash – A dog leash made of ghost net. Olive Ridley Project (ORP). Clitheroe, United Kingdom. Cited 31 May 2023. Available at https://www.oliveridleyproject.org/ghost-leash.

The non-profit organization The Olive Ridley Project (ORP) produces a "Ghost Leash", which is a dog leash made from 100 percent recovered and repurposed unwanted fishing net and waste fabric (Figure 25). The collection of raw materials and the production of the ghost leashes is undertaken in Pakistan by local fishing communities. Handcrafted by artisans, each dog leash is unique and may vary slightly in colour and design. The ORP Pakistan team and volunteers recover the unwanted fishing nets used in the production of the Ghost Leash from the sea and beaches near Abdul Rehman Goth, a fishing village in Keamari Town in Karachi.

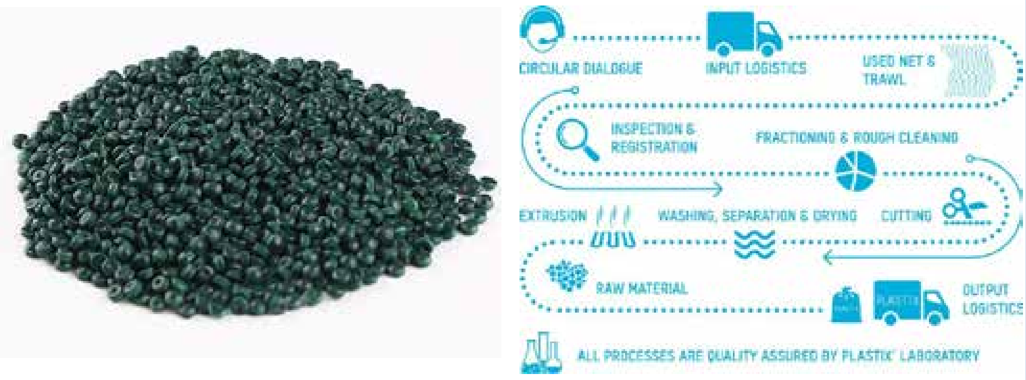
Abdul Rehman Goth is a centuries-old fishing village. It has a population of around 2 000 people and 300 fishing boats. Like so many traditional fishing communities, climate change, industrial fishing and overfishing have a major effect on this community. The ORP is working on ways to reuse ghost gear recovered in the area to provide an alternative income for the community. The nets are repurposed by the villagers: first the men clean and twist the nets into rope, and then the women stitch the fabric sleeves and wrap the Ghost Leash into the final product. All profits go back to the community.

2.3 MECHANICAL FISHING GEAR RECYCLING EXAMPLES: PLASTIX (DENMARK) AND KO WIN YANG INDUSTRIAL CO. LTD (TAIWAN PROVINCE OF CHINA)

This section provides practical examples of mechanical recycling technologies currently employed at the industrial scale for unwanted fishing nets in Denmark and Taiwan Province of China. Mechanical recycling processes for unwanted fishing gear are described in greater detail in Section 1.2.4.1.

Plastix, a Danish firm, mechanically converts unwanted fishing nets into recyclates in the form of a product called OceanIX®, which may then be utilized to make a variety of plastic goods. According to the company, utilizing the recyclate OceanIX® (which is comprised of high-density polyethylene, HDPE or polypropylene carbonate, PPC) instead of virgin plastic saves 1.65 tonnes of CO_2-equivalent emissions (Eurofish Magazine, 2017). However, these savings can only be realized if the raw material, unwanted fishing gear, can be gathered for recycling. In addition, Plastix supports a system that entails working with the marine and fishing industries, NGOs, harbours, and others to collect nets and ropes to be recycled (Figure 26). The unwanted fishing nets are sorted at the collection locations and then transported to the Plastix plant in Denmark (Eurofish Magazine, 2017). The material is then separated by polymer type and colour, shredded, cleaned, dried, and processed in an extruder to produce

FIGURE 26. PLASTIC RECYCLATE **OCEANIX®** AND THE PLASTIX OPERATIONS THAT CONVERTS WASTE INTO RAW MATERIAL. NETS AND TRAWLS ARE REDUCED TO **OCEANIX®**, WHICH CAN BE USED TO MANUFACTURE NEW PLASTIC PRODUCTS



Source: Modified and adapted from Eurofish Magazine (2017). Plastix' products contribute to improving the environment. Recycling discarded fishing gear. Eurofish Magazine, April 2017, 2 (C44346), 45-46. Available at https://eurofish.dk/recycling-discarded-fishing-gear/.

OceanIX® plastic pellets (Figure 26). Plastix also created an awards programme that provides certificates to its raw material (i.e. unwanted fishing nets) suppliers in three categories (bronze, silver, and gold). Certification allows them to document and market their efforts to clean up the environment by recovering unwanted fishing gear for recycling, reducing carbon dioxide emissions and conserving valuable resources.

Similarly, the Ko Win Yang Industrial Co. Ltd also produces equipment specially designed to recycle unwanted fishing nets mechanically (Ko Win Yang Industrial, 2023). The company was founded in 1980 in Taiwan Province of China and developed practical plastic crusher and integrated, turn-key washing and recycling lines for fishing net scraps (PA, PP, PE and other plastic materials). Using their equipment, it is possible to produce final products such as plastic flakes made from recycled fishing nets, which are directly available for extrusion–pelletizing, plastic fibres or other recycled plastic products.

2.4 CHEMICAL FISHING GEAR RECYCLING EXAMPLES: OCEANETS PROJECT

The OCEANETS project is included as an example of a collaboration between private industry and research institutions to support innovative chemical recycling technologies for unwanted fishing gear. The OCEANETS project, "Technological approaches for circular economy solutions in terms of prevention, recover, re-use and recycle of fishing gears to obtain added-value products in the textile industry" (http://oceanets.eu) is funded by the European Maritime and Fisheries Fund (EMFF). The aim of the project is to develop technology solutions, in line with the circular economy model, for end-of-life fishing nets. New methods are therefore being researched to prevent the loss of these nets and facilitate their recovery and reuse, as well as their recycling as new textile products with high added value.

The private fashion clothing and sportswear company – and project consortium member – EcoALF has developed chemical recycling technology to convert unwanted fishing nets into a new raw material in the form of polyamide pellets. As part of the project partnership, the plastic technology company and additional project member AIMPLAS developed a polymer tracker additive that can be added to these pellets so that, when exposed to infrared rays, the additive changes colour to reveal its presence in the fabrics. This industry research collaboration is the first time that it has been possible to demonstrate the traceability of the raw fishing gear material used to make a fabric (AIMPLAS, 2020). What is more, the OCEANETS programme also optimized a pilot plant to chemically recycle polyester and polyethylene from unwanted fishing gears to produce high-quality yarn.

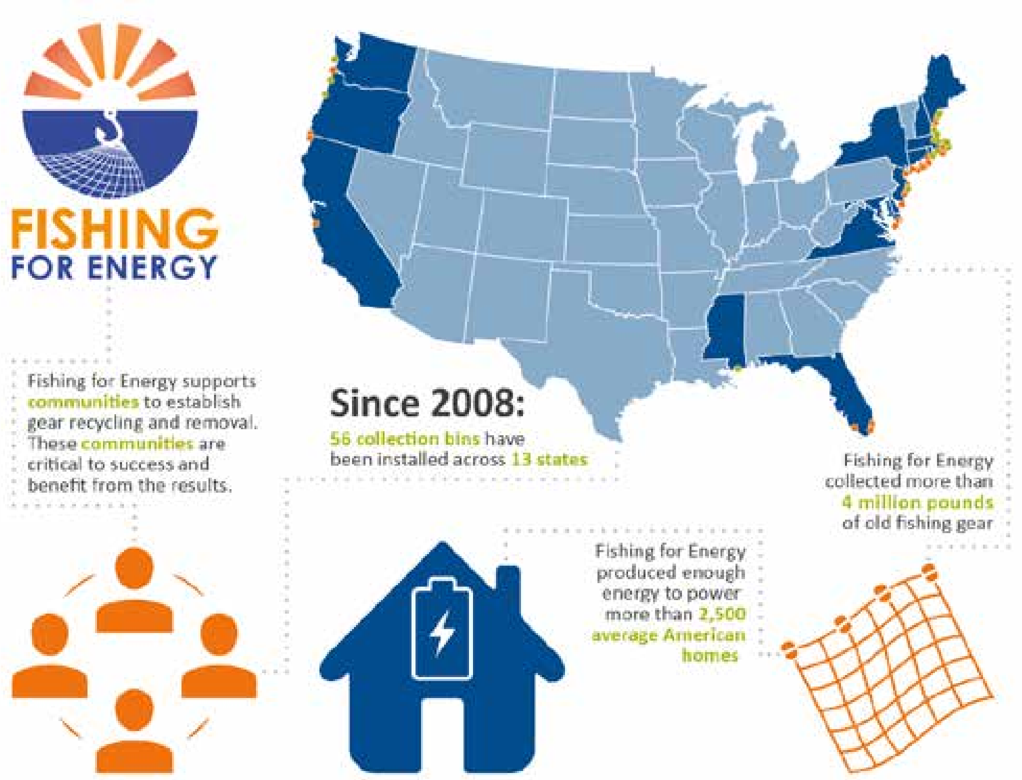
2.5 ENERGY RECOVERY FROM UNWANTED FISHING GEAR: FISHING FOR ENERGY AND HAWAI'I'S NETS TO ENERGY PROGRAMMES

The Fishing for Energy and Hawai'i's Nets to Energy programmes in the United States of America are included as examples of quaternary recycling processes (described in greater detail in Section 1.2.4.3), which support energy recovery from unwanted fishing gears.

Covanta Energy Corporation, the National Fish and Wildlife Foundation (NFWF), the National Oceanic and Atmospheric Administration (NOAA), and Schnitzer Steel Industries, Inc. launched the Fishing for Energy programme on the east coast of the United States of America in 2008. The immediate aim was to provide a no-cost solution for fishers to dispose of old, derelict, or unusable fishing gear and to reduce the amount of ALDFG (Morishige, 2010). Figure 27 shows a summary of the Fishing for Energy programme since 2008, including bins provided for unwanted fishing gear and energy produced across the United States of America. As part of this programme, gear collected at ports is initially sorted at the Schnitzer Steel facility where metals are recycled. The non-recyclable materials that remain, following this sorting and metal recycling, are then sent to various Covanta Energy locations for energy recovery.

The Fishing for Energy programme was modelled on Hawai'i's Nets to Energy programme. As part of the latter, Hawaiian longline fishers and the Northwestern Hawaiian Islands' multiagency marine debris group collect unwanted fishing nets

FIGURE 27. SUMMARY OF THE FISHING FOR ENERGY PROGRAM IN THE UNITED STATES OF AMERICA



Source: Adapted from NOAA (2023a). Fishing for Energy Infographic. Available at https://marinedebris.noaa.gov/sites/default/files/ffe-infographic-03312020.png

FIGURE 28. HAWAI'I NETS TO ENERGY BIN, LOCATED AT PIER 38 IN HONOLULU

Source: Adapted from NOAA (2023b). Hawai'i Nets to Energy Program. NOAA Marine Debris Program. Office of Response and Restoration. Available at https://marinedebris.noaa.gov/prevention/hawaii-nets-energy-program

and return them to a free disposal bin in Honolulu (Figure 28). When the bin is full of collected nets, the nets are transported to a Schnitzer Steel metal recycling facility, where they are prepared for energy recovery processes at a Covanta Energy facility. This collaboration initiative recycles an average of 80 tonnes of decommissioned nets and monofilament line each year. This initiative has generated enough electricity to power 283 families for a year since 2002 (Morishige, 2010).

2.6 OTHER INNOVATIVE PRODUCTS MADE FROM RECYCLED FISHING GEAR

A large variety of products can be made from recycling unwanted fishing gears. This includes but is not limited to the creation of pre-production pellets and flakes from mechanical (primary and secondary) processes, constituent monomers and polymers (chemical recycling) in tertiary processes and energy recovered from thermal conversion and quaternary processes. This section presents a diversity of examples of lesser-known products that are being or have been produced from recycling unwanted fishing gear to showcase opportunities for innovation.

2.6.1 India's fishers turn ocean plastic into roads

In June 2017, the Government of the State of Kerala in India, together with the Kollam District Fishing Boat Operators Association, launched the Suchitwa Sagaram ("Clean Sea") project. This project supports fishers to collect plastic waste from the ocean and bring it back to a local fishing harbour. From the harbour, the plastic waste is fed into a plastic shredding machine, which converts it into material that is then used for road surfacing. Since its launch, about 80 000 kg of plastic waste has been collected from the seas off Kollam, of which more than half was recycled to lay 84 miles (135 km) of road. Using recycled plastic is a cheaper alternative to conventional plastic additives for road surfaces. Every kilometre of plastic road uses the equivalent of 1 million plastic bags, saving around one tonne of asphalt. This also cuts costs by roughly 8–10 percent per kilometre of road paved with plastic, compared with a conventionally built road.

However, there has been some criticism of this project because of the reduction in quality of the plastics recycled into the road surface material, as well as the potential for the recycled plastic road material to act as a source of microplastic pollution.

2.6.2 Potential applications of 3D Printing for recycled fishing gears

Fused Filament Fabrication (FFF) 3D printers have risen in popularity, availability and affordability in recent years. As part of the Circular Ocean Project, funded by the European Commission, Hunt (2016a) and Hunt and Charter (2016) examined the potential of FFF 3D printing as a method of converting unwanted fishing gear polymers into commercial products. This included a qualitative assessment of the available fishing gear polymers, their composition, construction, condition and level of contamination, as well as an evaluation of their potential suitability as source material for FFF 3D printing filament.

There are a number of considerations to bear in mind when evaluating the success of unwanted fishing gear polymers in 3D printing applications,[23] and further research and experimentation is needed. Hunt (2016b) provides advice on the following key aspects:

- polyamide monofilament gillnet is likely to be the easiest fishing gear to process and is likely to produce high-quality 3D printing filament;
- a mechanized shredding process is recommended to prepare the fishing gear for processing, as opposed to cutting by hand;
- an industrial drying and pelletization process is likely to produce higher-quality filament, removing water content and ensuring a consistent composition and feed size; and
- further testing is required to identify the level of salt contamination and its impact on filament quality.

Products made by the company Fishy Filaments may also be utilized with 3D printers. Fishy Filaments, which has its headquarters in Cornwall, in the United Kingdom, seeks to improve the sustainability of the local fisheries by reducing waste and recycling nets more effectively. Following a year of process development, Fishy Filaments was formed in July 2017 and immediately started turning gathered nets into 3D-printer filaments with help from a crowdfunding campaign.

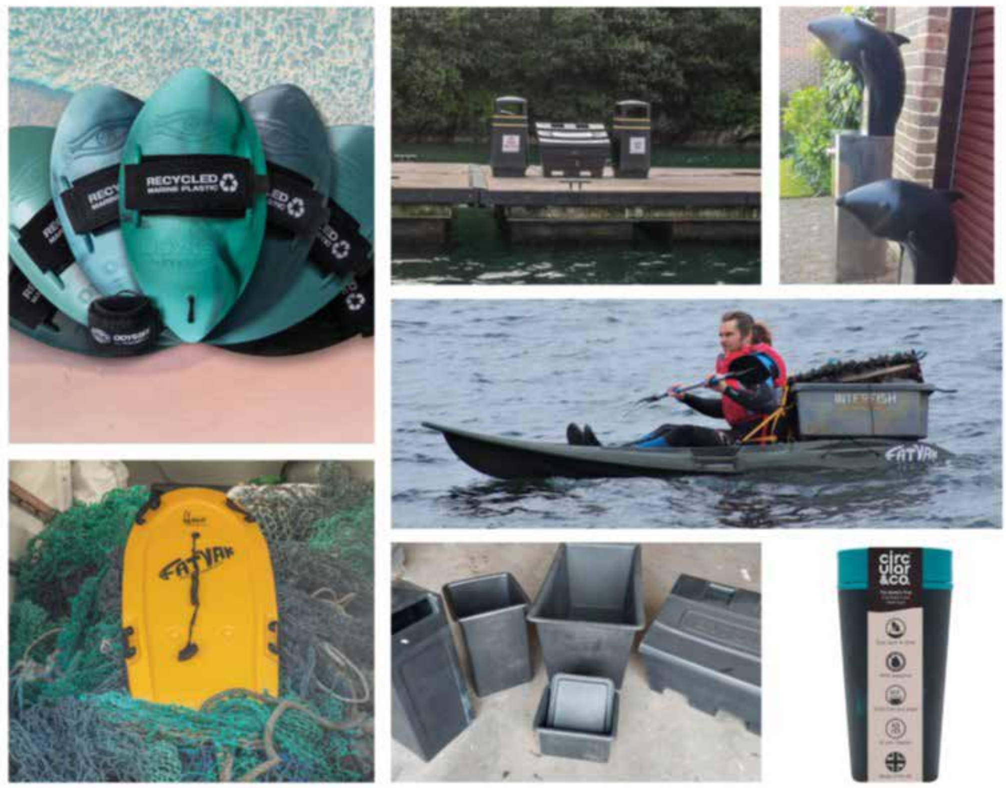
To gather end-of-life nets and ropes, Fishy Filaments collaborates closely with Newlyn Harbour, the regional fishing industry, and the South West Fishing for Litter initiative (see Section 2.1.4). Following sorting, grading, shredding, and washing (to remove salt and bio-fouling), Fishy Filaments converts recovered nets into clean, high-quality nylon "recyclates" (Figure 29). The main outcome of Fishy Filament's

FIGURE 29. FISHY FILAMENTS' RECYCLED NYLON, AND 3D PRINTER FILAMENT MADE FROM 100 PERCENT RECYCLED MARINE NYLON

Source: Modified and adapted from Fishy Filaments (2023). Recycled marine nylon converted into clean, high-quality nylon "recyclates". Materials for the future of manufacturing and the environment. Available at https://fishyfilaments.com

[23] Full details are outlined in Hunt (2016a) and Hunt and Charter (2016).

FIGURE 30. SOME OF THE MATERIALS PRODUCED BY ODYSSEY INNOVATION FROM RECYCLED UNWANTED FISHING GEARS IN THE UNITED KINGDOM



Source: Modified and adapted from Odyssey Innovation (2023b). Materials produced from recycled unwanted fishing gears. Available at https://www.odysseyinnovation.com

recycling process is a dimensionally correct raw material filament that can be utilized in Fused Deposition Modelling (FDM) 3D-printing.

2.6.3 Odyssey Innovation's kayaks, bodyboards and hand-planes

The company Odyssey Innovation collaborates with local fishing harbours in the United Kingdom to provide centralized drop off points around harbours for unwanted fishing gear. This gear is then collected across the ports and sent to facilities to be prepared for recycling. After recycling pre-processing is completed, the material is delivered to Plastix (see Section 2.3) for mechanical recycling. Following mechanical processing by Plastix, the unwanted fishing gear recyclates are then converted into kayaks, bodyboards, surfing hand planes/hand boards and a diversity of other products (Figure 30). Some of the profits from the sale of the kayaks are then used to pay for the programmes for collecting unwanted gear and cleaning up the environment.

2.6.4 Fashionably "Upcycling the Oceans" into unwanted fishing gear clothing

The EcoALF Foundation's Upcycling the Oceans initiative collaborates with local fishers, divers, volunteers and other partners in Greece, Italy, Spain, and Thailand to recover and collect unwanted fishing gears for recycling into their fashion clothing designs. The foundation also works with institutions that share its principles and aims to support awareness-raising initiatives around waste management, marine pollution and conservation, and research and development. In Spain for example, EcoALF works with 43 Spanish ports and has enlisted the help of almost 2 500 fishers to remove over 850 tonnes of marine litter; in addition, it uses the marine litter recovered to increase

FIGURE 31. EXAMPLES OF UPCYCLING THE OCEAN CLOTHING, WITH ENVIRONMENTAL MESSAGING REFERENCING THE SOURCE OF THE MATERIALS

Sources: Modified and adapted from Ourgoodbrands (2021). 100 percent recycled plastic fashion from the oceans. EcoALF, turning plastic bottle trash from the ocean into high quality fashion. Available at https://ourgoodbrands.com/ecoalf-100-recycled-plastic-fashion-oceans/. And PTT Global Chemical (2023). The Upcycling the Oceans, Thailand project. PTT Global Chemical. Available at https://sustainability.pttgcgroup.com/en/projects/10/the-upcycling-the-oceans-thailand-project.

knowledge and awareness-raising. Once collected the marine litter and unwanted fishing gear is chemically recycled to produce the polyester filaments used in the creation of their clothing. Figure 31 shows an example of the Upcycling the Oceans initiative and the clothing produced.

2.7 BLUE CIRCULAR ECONOMY (BCE) PROJECT

Section 1.4 of the report discusses the circular economy (CE) for unwanted fishing gear, including fishing gear design strategies and the development of circular business models (CBMs) to support the CE. The Blue Circular Economy (BCE) project is included to highlight a regional example of work undertaken to support the development of the CE for unwanted fishing gear.

The BCE was a three-year (2018–2021) transnational project co-funded by the European Union (EU) and Interreg Northern Periphery and Arctic Programme (NPA). It aimed to help small and medium-sized enterprises (SMEs) that offered products and services in the field of fishing gear recycling solutions in the NPA region to achieve greater market reach. To this end, the project set up a multilevel cluster to connect and catalyse SMEs in the region. The support included free assistance for the exploration and realization of business opportunities, including workshops, conferences, webinars, and one-on-one mentorship on how to turn used fishing gear into profitable ventures (Charter *et al.*, 2020). Partners in the BCE project included the Norwegian University of Science and Technology (Norway), Western Development Commission (Ireland), the Technical University of Denmark, and the Centre for Sustainable Design, University for the Creative Arts (United Kingdom) Environmental Research Institute.

An interesting open innovation for the creation of ideas, concepts, prototyping and testing of products was presented by Charter and Whitehead (2022) and named the BCE Lab©. The aim of the lab is to develop and commercialize new products (and possibly new circular business models) derived from/related to waste and "end-of-life" fishing gear. The BCE Lab© also aims to provide support to relevant organizations in a range of areas, from idea generation to company setup; to production and sales through advice on funding, collaboration, networking and marketing. Participants in a BCE Lab© could be start-ups, existing micro- or small businesses, social enterprises, and/or collaborative networks of entrepreneurs. They might include creative and design-oriented individuals, individuals with direct hands-on experience of processing unwanted fishing gear and/or able to oversee such work, individuals and groups with knowledge of recycling extruders and other equipment (including, potentially, 3D printers), and those with marketing and sales experience. The BCE Lab© includes four modules:

1. Design Lab: ideation, iteration and/or prototyping of solutions for any stage of the value chain for waste and “end-of-life” fishing gear.
2. Processing Lab: processing of waste and “end-of-life” fishing gear (e.g. by washing, drying, depolymerization) to provide “‘clean” materials, such as recycled pellets, filament or fibre to feed into manufacturers and B2B supply chains outside the BCE Lab© and/or into the Manufacturing Lab.
3. Manufacturing Lab: manufacturing and/or assembly operations that utilize waste and “end-of-life” fishing gear to produce products targeted at B2C, B2B or B2G (business-to-government) market.
4. Start-up Lab: an incubator or hub for start-ups and attracting existing micro-SMEs to relocate.

More information around circular business model opportunities for unwanted fishing gear can be found in Table 5 and Table 6 of Section 1.4.4.

3. Conclusions and recommendations

Fishing gear recycling can be undertaken through a wide array of technologies and processes, and can be supported by a similarly diverse range of technical measures and policy instruments. The background information on fishing gear recycling presented in this report contextualizes the various technologies available, and the circumstances under which they might be employed. The recycling method will depend upon the type, volume and quality of gears available for recycling, including its associated components, as well as local and regional capacities to support fishing gear recycling. The inclusion of, and communication between and across, a variety of stakeholders involved with fishing gear recycling is critical: policymakers, managers and regulators; fishing gear producers, manufacturers, assemblers, vendors and purchasers; fishers; port authorities; waste management agencies; and recycling businesses. Sound collaboration ensures that different stakeholders can support one another's efforts and roles in ensuring that fishing gear is responsibly and efficiently recycled at the end of its life according to the best available and most appropriate technology.

This report provides an overview of the current state of knowledge of fishing gear recycling, which can be used by a variety of stakeholders to better inform decisions around improving fishing gear circularity throughout its life cycle and to support fishing gear recycling at the end of its life. The report concludes with short discussions of practical examples of fishing gear recycling to showcase the variety of initiatives and options available globally.

Section 1.2 discusses the main recycling processes available for fishing gears. These include primary and secondary recycling (mechanical recycling), tertiary recycling (chemical recycling and thermal conversion, as well as the advanced physical recycling method of dissolution/solvent-based purification) and quaternary recycling (energy recovery). **The choice of the recycling method will depend upon the quality and nature of the materials of which the gear being recycled is made, as well as the available resources (waste management systems, technology and infrastructure) to support fishing gear recycling.**

While **primary and secondary recycling (mechanical recycling) processes are generally the most economical, widely known and available globally**, they **require multistage and labour-intensive pre-processing for fishing gears. Overall, they are also limited to less contaminated, less mixed material and mostly single polymer fishing gears**. The nature of the extrusion process allows for a wide variety of potential products, such as those summarized in Section 2.3 and Section 2.6. Secondary mechanical recycling outputs are sometimes criticized for not being truly circular, given that the resulting products are often of a lower quality, value and/or functionality compared to the fishing gear originally recycled.

Tertiary recycling processes (chemical recycling, thermal conversion and the physical dissolution/solvent-based purification processes) can complement mechanical recycling through their ability to recycle fishing gears and components that are not recyclable under primary and secondary processes, or to produce a higher-quality end product (e.g. in the case of depolymerization). Depolymerization is sometimes preferred for fishing gear materials that can be recycled through mechanical processes, as higher-value products are generated from the resulting monomers and polymers. Depolymerization processes that allow for the deconstruction and reconstruction of desired monomers and polymers indefinitely have been highlighted as potentially more circular recycling approaches, as they produce valuable monomers and polymers that can be used in the creation of new plastic fishing gears and components. At the time of this report, and based on the literature reviewed, depolymerization is the only process known to employ chemical recycling for the large-scale recycling of fishing gear and to use the secondary material stream for the production of new, high-quality fishing gear fibres.

Thermal conversion methods, which are often categorized as tertiary recycling, can also process more contaminated, mixed-material and mixed-polymer fishing gears that are either too complicated, labour-intensive or impossible to recycle using mechanical or depolymerization processes. Thermal conversion processes that result in the production of liquid and gaseous fuels are sometimes criticized as not being circular however, given the downcycled nature of the fuels produced. The European Union, for example, does not include fuel outputs from chemical recovery processes in their definition of tertiary recycling methods. Tertiary processes, particularly thermal conversion processes, can also result in the production of hazardous and toxic by-products that **require stringent pollution controls**. Tertiary recycling processes are additionally **energy-intensive and require expensive and highly specialized infrastructure**.

Quaternary recycling through incineration (i.e. energy recovery) can provide an alternative processing route for fishing gears that cannot be recycled through primary, secondary or tertiary processes. This process results in energy products in the form of heat, steam and electricity. However, **this report recommends that energy recovery processes only be considered if mechanical or chemical recycling options are not possible, and if the essential pollution controls and prevention measures are fully implemented.**

The range of technical measures and policy instruments summarized in Section 1.3 highlights the increasing **need for systemic approaches that align effective fisheries and waste management governance with complementary measures to support fishing gear recycling from the design and manufacturing stage through to end-of-life management**.

Measures that can be considered by fishing gear producers/manufacturers include: **using a less diverse range of material types and mixed plastic polymers in fishing gears; excluding non-recyclable materials in gear designs, as well as components and materials that are prone to being lost in the marine environment during gear use; improving the modularity of different gear components** to facilitate disassembly processes; **marking gears and components for commercial traceability; and labelling the material and polymer types that make up the gears**. Gear design and production that includes information for vendors, purchasers and users around anticipated gear and component lifetimes could assist fishers and regulators to ensure regular gear repairs and replacement during the use phase, as well as responsible return for recycling at their end of life. Relevant information would include the date of manufacture and recommended repair, in addition to replacement requirements and schedules.

Measures to be considered by fisheries and port authorities include: **fishing gear marking for owner identification and position at sea** as ALDFG prevention measures and to facilitate their recovery, **together with the provision of dedicated port reception facilities (PRFs) to collect unwanted fishing gears**. Wherever possible, EOLFG and recovered ALDFG should be collected separately, given the overall higher levels of contamination present in ALDFG compared to EOLFG. The provision of PRFs should be **coupled with complementary waste management systems that ensure the necessary preparation for, and transport to, recycling facilities.** Education and training for the personnel involved in preparing fishing gears for recycling, such as identifying fishing gear materials and basic polymer types present in various gears, can help to ensure more efficient and higher-quality pre-treatment processes. Stolte *et al.* (2019) also **recommend a combination of centralized and decentralized waste management infrastructure and logistics for unwanted fishing gear**, to allow for optimum and cost-efficient processing.

The implementation of **traceability system standards by policymakers, managers and regulators that identify and trace chemicals used in different plastic materials would also ensure the compatibility of recycled materials across local and regional regulations** (European Commission, 2018). This is especially important in industries where the plastic components in fishing gears include a wide range of additives.

Other measures that can be employed by policymakers, fisheries managers and, in some cases, port authorities include a range of **market-based instruments (MBIs). These provide financial support for fishing gear recycling initiatives by influencing the cost or market price of fishing gears, their material components and recycling services, as well as the development of Extended Producer Responsibility (EPR) schemes for fishing gears**. MBIs can facilitate economic feasibility for products made from recycled fishing gears and can help recycled plastic products to better compete in the market with new plastic products. Fishing gear "buy-back" programmes (also commonly referred to as "reward schemes"), deposit-refund schemes, and registration and deposit systems are some of the MBIs that can incentivize and provide funds for the return and collection of fishing gear for recycling. Alongside producer responsibility schemes, MBIs that can provide funds for recycling infrastructure and associated waste management systems include: environmental taxes, to raise revenue to support recycling logistics and infrastructure; "indirect" (also known as "no-cost") port waste fees and EPR schemes. The feasibility, effectiveness, financial benefits, fairness, social impacts, pricing, enforcement, acceptability and economic consistency of MBIs should be considered to determine which instrument might be best suited to incentivizing fishing gear recycling in a given country or region.

Financing and organizing systematic fishing gear collection and recycling and driving innovation in recyclable fishing gear design and end-of-life management can also be encouraged through EPR schemes. Given the often-complex production system for fishing gears, which can include different actors/businesses responsible for the design, manufacture, assembly and sale of different gear materials and components, it can be challenging to **determine the fairness, social impacts, enforcement and acceptability factors of EPR principles and schemes. These will vary depending upon the gear item, region and local fisheries context**. Regulatory measures that set mandatory levels for the utilization of recycled materials in new plastic products can also drive the market for recycled plastic products, including those derived from recycled fishing gear.

As indicated in Section 1.4, in order to align with the principles of the 2030 Agenda for Sustainable Development, **policy and regulatory decisions around fishing gear recycling should be underpinned and informed by circular economy (CE) models and principles wherever practical and possible. Circular economy models for fishing gears include fishing gear recycling as one option in a larger, more circular model of fishing gear life-cycle stages**. Waste hierarchy and R-based (e.g. 3R) models and concepts can complement CE models for responsible fishing gear management. Prioritization is given in this report to waste avoidance and reduction including at the fishing gear design stage, followed by reuse and recycling. The application of CE principles to fishing gear design, production, use and end-of-life management can improve opportunities for fishing gear recycling by leading to methods that are more circular and retain more of the original material and polymer value and performance quality. This approach supports a more holistic and sustainable life cycle for fishing gears in the long term.

The incorporation of product circularity measures can sometimes lead to trade-offs, however, and certain CE barriers will need to be considered in any transition to CE models for fishing gears. For example, Huang *et al.* (2019) detail how recyclability and durability choices interact in product design, including trade-offs between designing for improved recyclability. Simply increasing the amounts of fishing gear being recycled does not necessarily ensure the quality of recycled materials or demand for secondary raw materials. **The establishment of clear standards for the secondary materials produced, as well as ensuring the market viability of recycled products, will help the sustainability of circular business models for fishing gears**. Table 6 in Section 1.4.4 summarizes a variety of opportunities as well as threats for more circular business models for fishing gears. The Blue Circular Economy (BCE) project summarized in Section 2.7 in Part Two also provides a regional example of initiatives that support the integration of CE models for fishing gears, including supporting small and medium-sized enterprises (SMEs) to develop and market their recycled fishing gear products and services. Fishing gear life-cycle assessments (LCAs) can inform the development of CE strategies for fishing gears and help to ensure they are environmentally beneficial, economically feasible and socially acceptable.

The practical examples of fishing gear recycling in Part Two highlight the **diversity of fishing gear recycling options around the world**, from small-scale fishing gear collection and recovery initiatives to larger industrial, mechanical, chemical and energy recovery processes. One essential part of establishing globally responsible waste management systems for fishing gears will be building the technological and financial capacity to overcome the economic constraints and logistical difficulties that particularly affect lower-income countries and those heavily dependent on artisanal and small-scale fishing sectors.

While many opportunities exist for investments in fishing gear recycling, with a large variety of innovative products available for marketing, **market viability is also required for the variety of materials produced from the recycling processes**. This will ensure the demand for and financial viability of these initiatives. More precise estimates on the volumes of fishing gear material available for recycling at local and regional levels will help ensure a suitable and sustainable supply for recyclers. **Clear communication around the benefits of purchasing products made from recycled fishing gears** is important to ensure viable markets, especially if these products are more expensive than similar alternatives produced from raw materials and/or virgin plastics. Moreover, businesses do not always communicate the relative proportion of recycled to virgin plastic material in products made from recycled fishing gear in a transparent manner. As transparency is a condition of consumer confidence, changes in marketing campaigns are recommended to **reveal the actual percentages of the total recycled materials used in products that are advertised as being created from recycled fishing gears**.

Following Part Two, the Annexes provide additional technical information and considerations regarding fishing gear recycling that were beyond the scope of the main body of the report. **Annex 1 summarizes main tertiary recycling processes** and the advantages and disadvantages of different processes.

Annex 2 concludes the report with additional considerations shared by fishing gear recycling experts during a two-day webinar hosted by FAO in 2022. The webinar aimed to support the development of this report by asking fishing gear recycling experts to provide input on the report's themes, as well as filling the knowledge gaps it identified. While insights gained from the webinars have been integrated throughout this report, Annex 2 summarizes an assortment of additional elements discussed by webinar participants that have not been explored in detail here, but are included given their relevance to the fishing gear recycling topic. These include considerations around fishing gear recycling technologies in developing countries, education and awareness-raising initiatives to support fishing gear recycling, standards for improving circularity in fishing gears, biodegradable fishing gears and identification of funding priorities to support fishing gear recycling.


SOLUTION

4. References

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Annex 1. Description of main tertiary recycling processes

This annex describes in greater detail the main tertiary recycling processes outlined in Section 1.2.4.2. These processes include depolymerization (Annex 1.1), thermal conversion (Annex 1.2, noting that some regions such as Europe do not include these processes as recycling) and dissolution/solvent-based purification (Annex 1.3, noting that there is some debate as to whether this should be included as secondary or tertiary recycling). Advantages and disadvantages of these technologies are also summarized in **Table A1**.

ANNEX 1.1 DEPOLYMERIZATION

Depolymerization uses heat and chemical agents to break down polymers from pre-sorted plastic waste to their constituent monomers or shorter fragments of polymers (known as oligomers). Any remaining contaminants are removed following depolymerization so that the resulting monomers and oligomers can be used as secondary raw materials for plastic production (CEFIC, 2023a; The Consumer Goods Forum, 2022). The monomers produced act as the building blocks for plastic production and, as a result, the plastic products created from depolymerization are nearly identical to virgin plastics in terms of their physical and chemical qualities.

Depolymerization requires single, separately collected and pre-sorted polymers (i.e. monostream polymers) in the form of "condensation" polymers (or polycondensates).[24] The latter include polyesters (PET), polyamides (PA, e.g. nylon), and polyurethanes (PU). Depolymerization generally cannot accept many "addition" polymers,[25] which include polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC) (BPF, 2023; The Consumer Goods Forum, 2022). As such, this chemical recycling technology is **limited to pre-sorted, single polymer fishing gears composed of polycondensates,** and not available for other gears composed of mixed and/or addition polymers. At the time of this report, depolymerization is the only process that employs chemical recycling for the large-scale recycling of fishing gear and uses the secondary material stream for the production of high-quality fibres that can be used in new fishing gears.

At the industrial scale depolymerization is a widely applied technology that requires installations of sufficient size for a suitable volume of input streams and sufficient input material to be economically viable (Simon and Martin, 2019). It can therefore be challenging to undertake on a small scale, and depending upon the amount of solid waste needing to be recycled, and the infrastructure and resources available, it is not always economically viable (European Commission, 2020a). This can entail limitations for fishing gear recycling if the total collected EOLFG or (cleaned and sorted) recovered ALDFG supply is insufficient for the large industrial scale required. Centralized recycling infrastructure solutions are more likely for depolymerization processes that require larger volumes of unwanted fishing gear waste streams, as compared to decentralized, small-scale solutions (see Section 1.3.4 on Centralized and decentralized waste management infrastructure).

[24] Polymerization process of monomers being joined together with a small molecule, such as water or methanol, lost as a by-product Clark, J. 2021. Condensation polymerisation. Chemguide: Core chemistry 14-16, available at https://www.chemguide.uk/14to16/organic/condpolymers.html

[25] Double-bonded polymers formed by linking/chain reactions with other monomers without the production of any by-products Bishop. 2013. Addition (Chain-Growth) Polymers. *An introduction to chemistry* by Mark Bishop. Chiral Publishing Company, available at https://preparatorychemistry.com/Bishop_Addition_Polymers.htm

ANNEX 1.2 THERMAL CONVERSION

A variety of thermal conversion processes exist. The main processes available for EOLFG and recovered ALDFG include **pyrolysis** and **gasification** (including steam reforming). These processes can be used for **mixed and more contaminated polymers.** Thus, mixed polymer or more contaminated EOLFG and recovered ALDFG that cannot be recycled through mechanical processes (primary and secondary) or depolymerization (tertiary) have the potential to be processed using these thermal conversion technologies.

Pyrolysis is often also referred to as "thermal cracking",[26] and uses heat under anoxic (i.e. no oxygen) conditions to convert dry plastic input materials into basic hydrocarbons. These are then converted into a number of products including oils, light gases (sometimes used to power thermal processing activities) and ashes (in the form of "coke", for disposal) (BPF, 2023; The Consumer Goods Forum, 2022). The oils produced from pyrolysis can be used as fuel-based energy sources (The Consumer Goods Forum, 2022).[27] The relative fractions of solid, liquid and gaseous components are determined by temperature, heating and cooling curves, and time.

Target pyrolysis polymer feedstocks include polyethylene (PE), polypropylene (PP), polybutylene (PB), polystyrene (PS) and polymethylmethacrylate (PMMA) (BPF, 2023). While pyrolysis processes are suitable for the more complicated contaminated and mixed-polymer waste streams that are not possible under mechanical (primary and secondary) recycling processes, certain non-target polymers such as PET, PA and PVC can result in unwanted, sometimes hazardous by-products and emissions. As many unwanted fishing gears are comprised of PET and PA, concerns have been raised around the need to address the high toxicity levels that result if these polymers undergo pyrolysis (Stolte and Schneider, 2018). The presence of these non-target polymers can necessitate requirements for maximum inputs of these polymers,[28] as well as post-combustion cleaning or filtration stages. The large salt loads and other contaminants found in EOLFG and recovered ALDFG materials also require guarantees that no contaminants are transferred into the target products and resulting oil, ash (coke), and gas. In the case of chlorine and high metal loading, flue gas cleaning and post-washing procedures must be planned accordingly. Residual metals from fishing gears, particularly the lead pollution associated with lost gillnets, can additionally be recovered in the pyrolysis solid ash residue (coke), which may then be processed for metal recycling.

Gasification uses high temperatures with limited amounts of oxygen to break down mixed waste inputs,[29] including all types of plastics, into synthetic gases (i.e. syngas). These are made up of mixtures of hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2) (BPF, 2023; The Consumer Goods Forum, 2022). A pre-treatment stage is typically required to remove moisture from and increase the calorific value of the waste materials, and a gas cleaning system is required before the syngas can be used to produce new chemicals. The syngas produced can be used in a variety of applications, including for the production of chemicals that can be used in plastic production, as well as fuels that can be burned for energy (BPF, 2023; The Consumer Goods Forum, 2022).). Generally, gasification is only recommended if other recycling technologies

26 Pyrolysis processes occur between 400 °C and 800 °C (Dogu *et al*., 2021).

27 As mentioned earlier in the report, in Europe the definition of chemical recycling only includes the production of substances that can be used in the manufacturing of products (i.e. products or raw materials) and does not include fuel outputs. In other regions such as North America, chemical recycling does include fuel under the definition of "recycled" outputs (Chemical Recycling Europe, 2019).

28 For example, because PET crystallizes in condensation pipes and can clog output channels, several industrially utilized pyrolysis reactors now function with polymer mixtures dominated by polyolefins with a maximum of 10 percent PET in the input material (Stolte *et al.*, 2018).

29 Gasification processes typically occur at temperatures between 700 °C and 1 500°C IGES and ICLEI. 2021. Compendium of technologies for plastic waste recycling and processing. IGES Centre Collaborating with UNEP on Environmental Technologies (CCET) and ICLEI – Local Governments for Sustainability, South Asia. ICLEI South Asia, New Delhi, India. 68 pp. https://southasia.iclei.org/wp-content/uploads/2022/05/Technology_Compendium_Designed_Final.pdf.

are not possible, as these processes require large amounts of energy because of the high temperatures required and multiple stages to ensure full gasification/combustion of char (fixed carbon and ash) by-products.

A variety of gasification technologies exist. Mostly, these vary in the secondary stage following the initial semi-pyrolysis/vaporization of the feedstock and the production of the char by-products. During this second stage, the remaining carbon can be combusted with air or pure oxygen (this is frequently informally referred to as "**combustion**") to produce a nitrogen-rich, low-British Thermal Unit (BTU) fuel gas (from the air combustion) or a higher-quality mixture of carbon monoxide (CO) and hydrogen. The carbon can also be reacted with steam through a process commonly referred to as "**steam reforming**" to create an energy rich syngas.

Steam reforming is a type of hydrothermal processing which has been examined as a promising option to recycle EOLFG and recovered ALDFG. Steam reforming is a high-temperature vaporization method that uses the energy contained in polymers or other organic waste to split the strong hydrogen bonds between water molecules and reform these molecules into an energy-rich syngas (Stolte *et al.*, 2018).[30] Residual carbon is either linked to oxygen, generating CO_2, or to hydrogen, forming CH_4, leaving largely metal particles and sediments in the solid residue.

Steam reforming necessitates a humidity level of 25–30 percent (Dogu *et al.*, 2021). As such, it can be used for water-saturated EOLFG and recovered ALDFG items, as this process absorbs much of the water which might be found soaked into these gears. In contrast, the steam reforming of dry materials requires water injection to provide the oxygen and hydrogen necessary to break up polymer complexes into carbon and oxygen or carbon and hydrogen gaseous molecules. **When EOLFG and recovered ALDFG materials are blended, have high water saturation, and lead and/or organic contamination is substantial, steam reforming can be a useful approach for energy recovery from these materials, in addition to recovering any metal and lead components for subsequent recycling.** The high temperatures employed in steam reforming can also eliminate harmful emissions that result from lower-temperature processes such as pyrolysis and require extra filtration processes. For example, experiments using an ultra-high temperature steam reforming reactor (UHTH) at 1 100°C to treat heavily polluted gillnet samples resulted in the dissolution of long-chained compounds into basic constituent chemicals without any harmful emissions (Stolte *et al.* (2018). However, 100 percent calorific value conversion from raw materials to syngas is not possible, and the proportion of energy entering the syngas is currently unclear in many processes. Moreover, the calorific content of some recycled gears is only partially able to offset the high-energy inputs required by these high-temperature thermal processing approaches (Schneider, 2020).

ANNEX 1.3 DISSOLUTION/SOLVENT-BASED PURIFICATION

Dissolution or solvent-based purification (terms often used interchangeably) immerses pre-sorted plastic waste materials in selective solvents along with some heat to dissolve the plastics into solutions of their constituent polymers, and additives. The structures of the polymers remain unaltered. After the additives and any contaminants are removed, these polymers are then reformulated with new additives into new plastic products (BPF, 2023; CEFIC, 2023b). Dissolution technologies are still relatively new, in developmental and pilot stages, and they rely heavily on solvents that act selectively to separate the desired polymers. Target feedstocks include polyvinyl chloride (PVC), polystyrene (PS), polyethylene (PE) and polypropylene (PP) (BPF, 2023; Dolan, 2022). As highlighted in Section 1.2.4.2, to the best of the authors' knowledge, and based on available research, at the time of this report dissolution has not been trialled for fishing

[30] Steam reforming processes occur between 1 000 °C and 1 300°C (Dogu *et al.*, 2021).

gear recycling. However, it has been included by virtue of its applicability to plastic recycling and the chance that such applications might be trialled or extended to fishing gear in the future.

While this plastic processing technology is often included in summary descriptions of chemical (tertiary) recycling processes, it is actually a physical not a chemical process. As such, many argue that it should not be included under the umbrella of chemical recycling technologies (see Section 1.2.4.2). However, its broad inclusion and the frequent references to it in technical and grey literature, and indeed in chemical recycling discussions (Dolan, 2022; Hann and Connock, 2020; Manzuch *et al*., 2021; The Consumer Goods Forum, 2022) justify its brief inclusion in this report.

ANNEX 1.4 ADVANTAGES AND DISADVANTAGES OF CHEMICAL RECYCLING TECHNOLOGIES

Table A1 summarizes the main advantages and disadvantages of the three chemical recycling technologies outlined in this report. Because this table was modified from Hann and Connock, 2020, some of the terms are slightly different than those employed above. Chemical depolymerization in the table refers mostly to the use of depolymerization (Annex 1.1), thermal depolymerization refers to pyrolysis techniques (Annex 1.2) and solvent purification refers to dissolution/solvent-based purification (Annex 1.3). This table is included to summarize chemical recycling processes more broadly and is not specific to fishing gears.

TABLE A1. SUMMARY OF ADVANTAGES AND DISADVANTAGES OF CHEMICAL RECYCLING TECHNOLOGIES

Chemical depolymerization		**Thermal depolymerization**		**Solvent purification**	
Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Monomer outputs can be utilized to produce plastic products of equal quality to virgin equivalents. Demonstrated examples of systems that allow the recovery and reuse of chemical reagents such as catalysts and solvents. High yields demonstrated for a number of technologies. Demonstration of commercial viability for bottle and fibre inputs.	Technologies typically require homogenous waste streams as an input, often demanding extensive pre-treatment/ sorting technologies. Lack of information concerning the quantities of chemical reagents and other supplementary materials e.g. catalysts. Lack of clarity as to the overall energy inputs associated with the technologies; processes often require high energy inputs. Lack of yield information at the plant level. General lack of understanding around the level of contamination that the technologies can handle, nor how the contaminants are dealt with following monomer purification. Little consideration given for hazardous inputs/by-products. Lack of verified environmental performance data for the majority of technologies.	Technology can typically accept more heterogenous mixtures of waste as an input, but at the expense of output quality and utility (recovery as a fuel). Can be applied to waste streams that are currently unrecyclable. When purified, outputs can be used to manufacture plastics and other high-value chemicals of equal quality to virgin feedstocks. High temperatures utilized to effectively decontaminate the waste inputs.	Requires a homogenous source of plastic waste to provide higher level (i.e. monomer) outputs. The random nature of the depolymerization process leads to a complex mixture of products, requiring costly purification systems to isolate usable products. Current thermal depolymerization outputs are skewed towards the lower cost production of fuel. No clarity as to the recycling of by-products and reagents as part of the process. Steam cracking of pyrolysis oil to create monomers typically results in a proportion of the input being converted to energy (recovery) to run the process. Requires existing virgin polymer value chain to produce monomers. No environmental performance data currently available for the majority of technology providers.	Has been demonstrated to separate polycotton textile blends. Environmentally benign solvents have been tested successfully at a lab scale. Generally allows recovery of the solvent for reuse. Demonstrated to recover non-target by-products for valorization.	Can currently handle only material inputs that are largely homogenous in nature. Often requires stringent pre-sorting and or pre-treatment steps to prepare for purification. Typically necessitates high energy requirements, in particular the post-purification drying stages. Typically, cannot remove contaminants entirely. Has not been demonstrated to provide food-grade outputs. Lack of clarity regarding the solvent types and toxicities for larger-scale technologies. Does not allow for limitless recycling of the material, because of the thermal degradation of the chains during reprocessing to form new plastics. Current lack of clarity regarding environmental performance. Yet to demonstrate economic viability on a commercial scale.

Source: Hann and Connock (2020). Chemical Recycling: State of Play. Eunomia, C. Trust. Available at https://chemtrust. org/wpcontent/uploads/Chemical-Recycling-Eunomia.pdf.

Annex 2. FAO fishing gear recycling webinars

Two webinars were organized on 10-11 October 2022 to support the development of this report and fill the knowledge gaps it prompted. The first webinar focused on technical and scientific discussions related to fishing gear recycling methods, policies, Extended Producer Responsibility (EPR), product circularity, and reception of unwanted fishing gear in ports. In the second webinar, invited speakers presented practical examples of fishing gear recycling initiatives around the world, and identified challenges and opportunities associated with fishing gear collection and recycling.

While key insights gained from the webinars have been integrated throughout this report, this Section summarizes an assortment of additional elements discussed by webinar participants that have not been explored in detail; they are included here given their relevance to the fishing gear recycling topic. These include considerations around **unwanted fishing gear recycling technologies in developing countries, education and awareness-raising initiatives** to support fishing gear recycling, **standards for improving circularity** in fishing gears, **biodegradable fishing gears** and the identification of **funding priorities to support fishing gear recycling**.

Many developing countries face unwanted fishing gear management challenges due to a lack of financing, including for necessary recycling infrastructure and training. This can result in inadequate waste collection systems, including for unwanted fishing gears, the dumping and burning of waste in open spaces, the operation of uncontrolled or controlled dumpsites, and limited-to-no waste recovery and recycling. Governments have an important role to play in the improved management of unwanted fishing gear through appropriate policy development and implementation. **It is important for waste management practitioners in developing countries to share and publish their work so that others may learn from their insights. Global communities of practice that aim to improve waste management in developing countries can be supported**. The digital platform established by the UNEP-led Global Partnership on Plastic Pollution and Marine Litter (https://digital.gpmarinelitter.org/about-us) provides a comprehensive platform for this exchange of knowledge and information.

Webinar participants also highlighted **the importance of education and awareness-raising initiatives** around the harmful environmental and socioeconomic effects of ALDFG, responsible collection and recycling of unwanted fishing gear, and opportunities provided by fishing gear recycling **to motivate better fishing gear stewardship and improve collection and recycling opportunities**. Fishers who return their unwanted fishing gears for recycling at their end of life can also be informed about the resulting products made from their recycled gears, as well as the recycling pathways undertaken.

Another topic of discussion throughout the fishing gear recycling webinars, which has not been examined in detail in this report, was the opportunity **to develop common standards for fishing gear circularity and recyclability at national, regional and global scales**. For example, webinar participants shared that in Europe, the European Committee for Standardization (CEN, its acronym in French), established a Technical Committee to address different aspects of developing standards for circular fishing gear. Various standards are in development across CEN working groups (CEN, 2020).

Most notably, the CEN/TC 466/WG 2 provides standards for the recyclability of plastic-based materials in fishing gear and aquaculture equipment (CEN, 2020).[31] The British Standards Institution similarly established a committee (SCP/1/4/1) to establish standards for the circularity and recyclability of fishing gear and aquaculture equipment to contribute to CEN's standards. Some webinar participants noted the opportunity for the development of a global standard for the circular design of fishing gear, including a "product passport" that requires clear labelling of the contents of the fishing gear. The International Organization for Standardization (ISO) was mentioned as a possible starting point for such an undertaking, noting that the ISO 14021:2016 (Environmental labels and declarations-Self-declared environmental claims) currently includes standards for environmental labelling, as well as product declarations and footprints (ISO, 2016).

There was also discussion among participants regarding the opportunities and challenges to develop **biodegradable fishing gears**, in order to minimize environmental impacts if they are abandoned, lost or discarded to the marine environment. Participants discussed that fishers need to be confident that the material they are using will perform well for fishing. If the material being used biodegrades in the marine environment, then fishers may need to replace their gear more frequently. Workshop participants also highlighted concerns that biodegradable materials for fishing gears may lack the durability of their plastic equivalents, may be more expensive or may contain a mixture of biodegradable and non-biodegradable materials, which can result in more complicated and expensive recycling efforts. These limitations can delay the uptake and acceptance of these changes by the industry.

Webinar participants shared that the ongoing "The E-Redes" project in Portugal promotes the use of biodegradable nets. This project supplies gillnets and trammel nets made with a biodegradable resin to the local fishing community to reduce ghost fishing and the introduction of synthetic plastic material into the ocean. The study undertaken by the project evaluates the physical properties and durability of innovative monofilaments, the feasibility of manufacturing fishing gear with biodegradable monofilaments, and the fishing efficiency of nets constructed from biodegradable monofilaments compared to conventional nets. The collaborative initiative **Dsolve** is also exploring opportunities to replace traditional plastic materials in fishing gears with biodegradable materials.

Finally, while this report does discuss the opportunities to support fishing gear recycling initiatives financially through market-based instruments, EPR schemes and policy and regulatory measures (Sections 1.3.5–1.3.7), as well as opportunities and challenges for the circular business models that support fishing gear recycling (Section 1.4.4), it does not make recommendations for funding priorities to support fishing gear recycling. Webinar participants were also asked to identify and discuss these funding priorities. To facilitate the development and redesign of fishing gear and its constituent materials, webinar participants highlighted that **proper testing and dedicated funding for research and innovation** are required. Support is required for fishing gear trials and pilot studies that aim to better understand the resources required for – and effectiveness of – new technologies that support EOLFG and recovered ALDFG recycling, without impacting fishing efficiency and fishing gear lifespan. Participants noted that further investments should also be made in **training for fishing gear manufacturers and assemblers related to environmentally conscious circular design**. Additional funding priorities mentioned by participants included: the research and development of recyclable and/or biodegradable materials for fishing gears; testing the utility of using high quality recyclates within the production of new fishing gears; and projects that develop design methods that **increase the overall lifespan of fishing gears**.

[31] CEN/TC 466/WG 2 (Environmental and circular requirements for fishing gear and aquaculture equipment) is a working group attached to the CEN/TC 466 Technical Committee (Circularity and recyclability of fishing gear and aquaculture equipment).

GloLitter partnerships

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