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Environmental Product Declaration of Nautical Ropes: A Multi-Impact Category Analysis Through Life Cycle Assessment

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Abstract. Sustainability and climate change represent increasingly critical challenges for contemporary society. This reality demands the development of low environmental impact products and production processes, with particular attention to reducing CO_2 emissions. To achieve this goal, it is essential to gain an in-depth understanding of the environmental impact associated with each product and production process. In this regard, the calculation of the environmental impacts through LCA (Life Cycle Assessment) model applied to marine components has been performed, with a specific focus on two sailing ropes used in sailboats. LCA was conducted following the PCR (Product Category Rules) specific to the maritime sector with the aim of developing an EPD (Environmental Product Declaration) under the ISO 14025 standard. Three different lifecycle phases were analyzed, i.e., Upstream, Core, and Downstream, representing the main phases involved in products lifetime. Particular attention was paid to estimating the impact of transportations, both from the supplier to the manufacturer and from the manufacturer to the final customer. This study highlighted the added value provided by the evaluation of various environmental impact categories, including aquatic ecosystems, acidification, and water usage, in addition to the well-known Global Warming Potential (GWP). The results revealed that most of the impacts are generated during the Upstream processes, which include raw material extraction and associated transportation. In conclusion, this study emphasizes the importance of the LCA methodology, which provides a detailed assessment of environmental impacts across multiple indicators.

Keywords. Sustainability, Life Cycle Assessment, Product Category Rules, Ropes, Environmental Product Declaration, Naval, Ship

1. Introduction

The maritime sector plays a fundamental role in the global economy, supporting international trade and mobility. However, it also generates substantial environmental impacts throughout the ship life cycle, from construction to decommissioning, which can be evaluated through Life Cycle Assessment (LCA), a science-based methodology for quantifying environmental burdens [1]. In naval applications, LCA enables the identification and mitigation of impacts, fostering sustainable development within the

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industry [2]. To date, most LCA studies in the nautical sector have focused on vessels as whole systems [3,4], with the goal of generating reference data and guiding sustainability decisions. This study addresses a less-explored area: the environmental analysis of naval components, specifically ropes used in sailing and motor vessels. The aim is to raise awareness among maritime stakeholders on the value of LCA for responsible resource management and transparent production processes [5]. Particular attention is given to the analysis of greenhouse gas emissions and issues related to climate change, highlighting the environmental performance of different materials used in rope manufacturing.

2. Materials and Methods

This study presents a detailed LCA calculation of nautical ropes produced by Armare S.r.l., a key supplier in the maritime sector [6]. As no specific Product Category Rules (PCR) exist for ropes, the assessment followed the naval PCR framework [7,8], ensuring methodological consistency and result reproducibility. The analysis was conducted in accordance with ISO 14040 [9], ISO 14044 [10], and GPI 4.0 [11], and was independently verified by a third-party certification body.

The environmental impact analysis was conducted using the SimaPro v9.5.0.0 software and the Ecoinvent v3.9.1 database, both widely recognized for reliability and accuracy. Two nautical ropes were investigated: Dyneforce 78, made with high-tenacity polyethylene (UHMWPE) yarn, with a 6 mm diameter, 4.995 daN breaking load, and a mass of 24 g per meter; and Star, made with high-tenacity polyester yarn, with a 10 mm diameter, 2.450 daN breaking load, and 75 g per meter. For both, the functional unit adopted was 1 meter of rope, enabling a consistent basis for comparison across the study.

The two ropes follow different production processes. Dyneforce 78 is made from 12 strands of Dyneema® yarns, processed through twisting, braiding, heat treatment, and final impregnation with a polyurethane-based coating. Star, in contrast, is a double-braided polyester rope manufactured through twisting and braiding operations. The LCA model accounts for the environmental impact of each manufacturing phase, including packaging. For Dyneforce 78, packaging consists of a 320 g spool (polypropylene and polystyrene) holding 200 meters of rope, while Star uses a larger 650 g spool. Packaging was divided into specific and generic types: the spool was modelled as specific packaging, while generic packaging includes cardboard boxes, polyethylene film, and adhesive tape. Although generic packaging represents less than 1% of the final product weight and is excluded from content declarations per GPI 4.0 [11], it was included in the impact calculations.

To ensure a comprehensive LCA, environmental data were classified into three categories: specific, selected generic, and proxy data, in accordance with GPI 4.0 [11]. Specific data, also referred to as primary data, were directly collected from the rope production facility and include measurements related to process inputs, energy use, and waste. Proxy data, used only in maintenance-related activities, were derived from secondary sources that do not fully meet the quality requirements defined for selected generic data; their use remained below the 10% threshold, as prescribed by PCR rules. Selected generic data, meeting high standards for completeness, representativeness, and methodological rigor, were applied to model Dyneema®, which is not available in the Ecoinvent database. Its base chemical structure and production pathway were reconstructed from recent literature [12]. Dyneforce ropes are manufactured via a patented gel spinning process [13], whereby the UHMWPE polymer is not extruded as a molten mass but spun from a gel due to its extremely high molecular weight, which prevents conventional melt processing. The conducted LCA analysis follows a cradle-to-grave system boundary, encompassing all upstream, core, and downstream processes, as specified by the relevant PCR [8]. The cradle-to-grave system boundaries for the two nautical ropes under investigation are reported in Figure 1 and Figure 2.

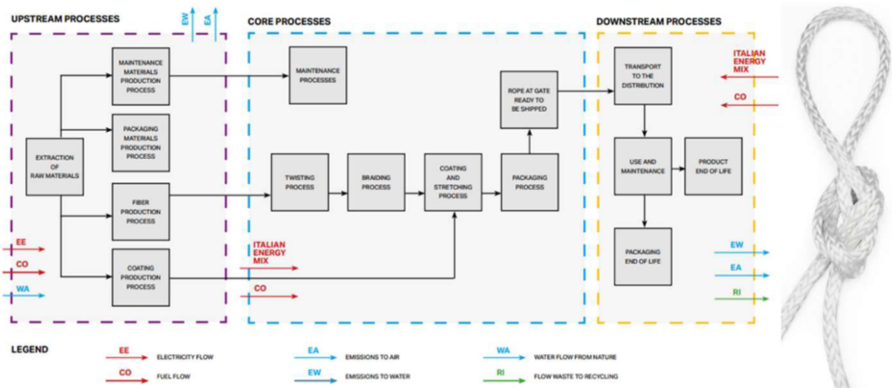

Figure 1. System boundaries of nautical rope "Dyneforce 78"

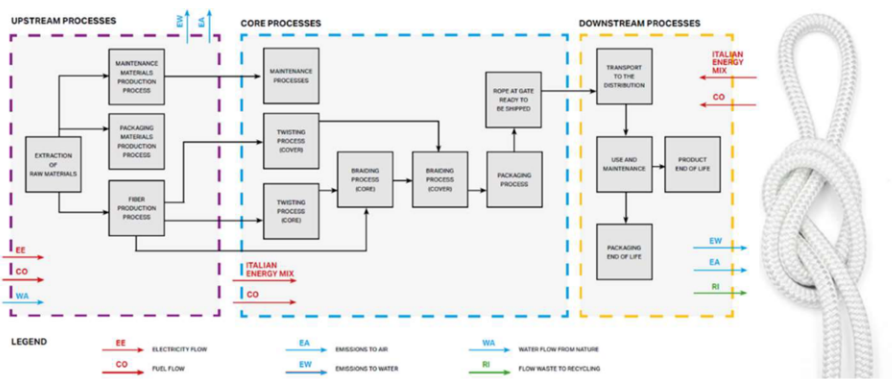

Figure 2. System boundaries of nautical rope "Star"

Flows excluded under the <1% cut-off rule include the transport of polymers used to produce packaging materials and the raw inputs for cardboard and wooden packaging. The LCA was developed using an attributional approach, with environmental burdens allocated based on product mass. In multi-output processes, a mass-based allocation criterion was adopted to distribute impacts among co-products. The life cycle inventory (LCI) was built using company accounting records, invoices, and utility bills from 2023, referring to the full 12-month period of 2022. Primary data were used for all core-phase operations, with site-specific measurements taken at the production facility. For energy-related impacts, the ecoinvent Italian residual mix was adopted as the reference electricity profile for core processes. Given the variability in rope diameters and associated energy requirements, direct measurements were taken on the machinery during the processing of Dyneforce 78 and Star ropes. Energy consumption was then allocated based on the formula:

$$E_{plant} = E_{twisting} + E_{braiding\ process} + E_{coating} + E_{general\ services}$$

where each term represents the energy consumed during each operation, and the allocation was made relative to the mass of rope processed during each phase. This approach allowed for precise estimation of the specific energy consumption per product, ensuring greater accuracy in energy-related environmental impact calculations. For the end-of-life phase, both ropes and their plastic-based packaging were modelled using global municipal waste management data from the 2024 Global Waste Management Outlook [14], where the waste treatment scenario considered 48.4% landfill, 21% incineration, and 30.6% recycling. It was assumed that discarded ropes are typically routed through municipal waste systems at marinas or ports. Environmental leakage was excluded from the model, as it is neither controlled nor reliably quantifiable. Table 1 illustrates the breakdown of the upstream, core, and downstream phases for the two nautical ropes.

Table 1: Breakdown of main LCA phases

Upstream	Core	Downstream
- Raw material extraction and production fibre production - Semi-finished product production - Reuse processes of materials from other production activities - Production of packaging for distribution and consumption - Production of maintenance materials for central processes - Generation of electricity and production of fuels, steam and other energy carriers used in upstream processes - Production of semi-products used in central processes - Transport outside the core processes (including electricity generation production of fuels and other energy carriers used in this transport)	- Generation of electricity and production of fuels, steam and other energy carriers used in main processes - Production of semi-finished products - Rope assembly: twisting and braiding - Heat treatment - Surface treatment: impregnation of the top- packaging process, - Plant and machine maintenance - Treatment of waste generated during production	- Transport of the product to the retailer/consumer - Use of the product, e.g. use of electricity or water, use activities that cause direct emissions, maintenance activities, and - End-of-life treatment of the used product and its packaging, including transport - Generation of electricity and production of fuels, steam and other energy carriers used in downstream processes.

3. Results and Discussion

Table 2 and 3 report the results of the life cycle impact assessment for the products under examination, i.e., the Dyneforce 78 nautical rope made of polyethylene (UHMWPE) and the Star nautical rope made of polyester.

Table 2. Life Cycle Impact Assessment results of rope model "Dyneforce 78"

PARAMETER		UNIT	Upstream	Core	Downstream	TOTAL
Global warming potential (GWP)	Fossil	kg CO_2 eq.	$3{,}73*10^{-1}$	$1{,}49*10^{-1}$	$0{,}17*10^{-1}$	**$5{,}39*10^{-1}$**
	Biogenic	kg CO_2 eq.	$0{,}59*10^{-2}$	$0{,}81*10^{-2}$	$0{,}97*10^{-2}$	**$1{,}18*10^{-2}$**
	Land use and land transformation	kg CO_2 eq.	$5{,}25*10^{-4}$	$0{,}21*10^{-4}$	$0{,}08*10^{-4}$	**$5{,}54*10^{-4}$**
	TOTAL	kg CO_2 eq.	$3{,}67*10^{-1}$	$1{,}57*10^{-1}$	$0{,}27*10^{-1}$	**$5{,}51*10^{-1}$**
Ozone layer depletion (ODP)		kg CFC 11 eq.	$2{,}28*10^{-3}$	$0{,}48*10^{-3}$	$0{,}09*10^{-3}$	**$2{,}85*10^{-3}$**
Acidification potential (AP)		mol H+ eq.	$0{,}99*10^{-4}$	$0{,}26*10^{-4}$	$0{,}01*10^{-4}$	**$1{,}25*10^{-4}$**
Eutrophication potential (EP)	Aquatic freshwater	kg P eq.	$4{,}52*10^{-4}$	$0{,}94*10^{-4}$	$0{,}39*10^{-4}$	**$5{,}86*10^{-4}$**
	Aquatic marine	kg N eq.	$4{,}40*10^{-3}$	$0{,}94*10^{-3}$	$0{,}39*10^{-3}$	**$5{,}72*10^{-3}$**
	Aquatic terrestrial	mol N eq.	$2{,}03*10^{-3}$	$0{,}42*10^{-3}$	$0{,}14*10^{-3}$	**$2{,}59*10^{-3}$**
Photochemical oxidant creation potential (POCP)		kg NMVOC eq.	$1{,}11*10^{-6}$	$0{,}00*10^{-6}$	$0{,}00*10^{-6}$	**$1{,}11*10^{-6}$**
Abiotic depletion potential (ADP)*	Metals and minerals	kg Sb eq.	$2{,}07*10^{-6}$	$0{,}98*10^{-6}$	$0{,}05*10^{-6}$	**$3{,}10*10^{-6}$**
	Fossil resources	MJ, net calorific value	7.28	2.21	0.21	**9.69**
Water deprivation potential (WDP)*		m^3 world eq. deprived	$1{,}05*10^{-1}$	$0{,}39*10^{-1}$	$0{,}01*10^{-1}$	**$1{,}45*10^{-1}$**
Particulate Matter		Disease inc.	$1{,}86*10^{-8}$	$0{,}24*10^{-8}$	$0{,}64*10^{-8}$	**$2{,}75*10^{-8}$**

Table 3. Life Cycle Impact Assessment results of rope model "Star"

PARAMETER		UNIT	Upstream	Core	Downstream	TOTAL
Global warming potential (GWP)	Fossil	kg CO_2 eq.	3,67*10^{-1}	1,32*10^{-1}	0,21*10^{-1}	**5,20*10^{-1}**
	Biogenic	kg CO_2 eq.	-0,01*10^{-1}	0,03*10^{-1}	0,03*10^{-1}	**0,05*10^{-1}**
	Land use and land transformation	kg CO_2 eq.	2,16*10^{-4}	0,19*10^{-4}	0,03*10^{-4}	**2,38*10^{-4}**
	TOTAL	kg CO_2 eq.	3,66*10^{-1}	1,35*10^{-1}	0,24*10^{-1}	**5,25*10^{-1}**
Ozone layer depletion (ODP)		kg CFC 11 eq.	0,95*10^{-3}	0,44*10^{-3}	0,04*10^{-3}	**1,43*10^{-3}**
Acidification potential (AP)		mol H+ eq.	12,70*10^{-5}	2,35*10^{-5}	0,05*10^{-5}	**15,10*10^{-5}**
Eutrophication potential (EP)	Aquatic freshwater	kg P eq.	2,86*10^{-4}	0,80*10^{-4}	0,42*10^{-4}	**4,08*10^{-4}**
	Aquatic marine	kg N eq.	2,18*10^{-3}	0,84*10^{-3}	0,15*10^{-3}	**3,18*10^{-3}**
	Aquatic terrestrial	mol N eq.	2,89*10^{-3}	0,37*10^{-3}	0,05*10^{-3}	**3,32*10^{-3}**
Photochemical oxidant creation potential (POCP)		kg NMVOC eq.	1,01*10^{-8}	0,31*10^{-8}	0,01*10^{-8}	**1,33*10^{-8}**
Abiotic depletion potential (ADP)*	Metals and minerals	kg Sb eq.	0,65*10^{-6}	0,90*10^{-6}	0,02*10^{-6}	**1,57*10^{-6}**
	Fossil resources	MJ, net calorific value	6.46	1.97	0.08	**8.5**
Water deprivation potential (WDP)*		m^3 world eq. deprived	3,58*10^{-1}	0,36*10^{-1}	0,01*10^{-1}	**3,95*10^{-1}**
Particulate Matter		Disease inc.	0,75*10^{-8}	0,21*10^{-8}	0,21*10^{-8}	**1,17*10^{-8}**

The interpretation, conducted in line with ISO 14044 [10], includes the identification of key impact contributors, completeness verification, sensitivity and data quality assessments, and consistency checks against sector benchmarks. It concludes with final considerations, limitations, and recommendations. Figure 3 illustrates the gravity analysis for the Dyneforce 78 rope (6 mm diameter), highlighting the key environmental hotspots. As expected, fiber production emerges as the primary contributor across most impact categories, mainly due to the energy-intensive processes required to manufacture UHMWPE. In addition, the detailed assessment of operational energy consumption shows that electricity used during the coating and stretching phases also contributes significantly to the overall impact, particularly when compared to the other manufacturing steps.

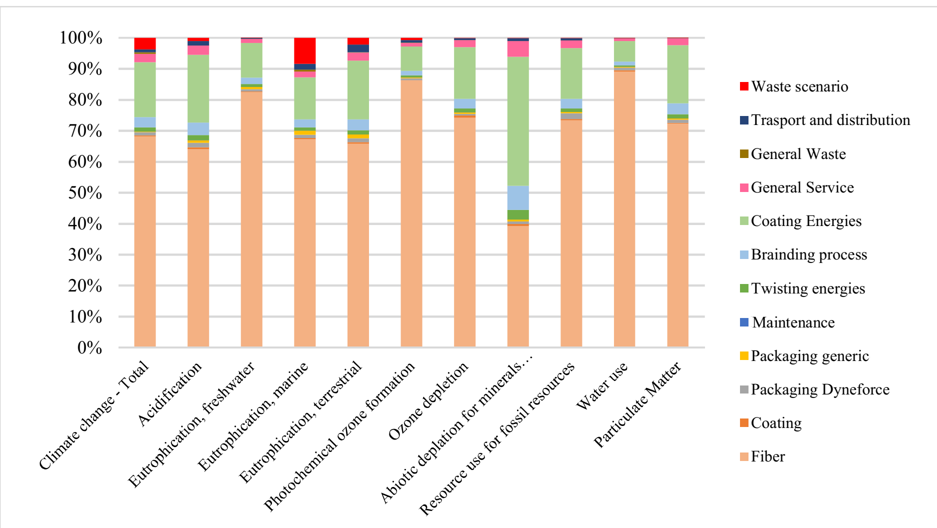

Figure 3. Dyneforce gravity analysis

Figure 4 presents the gravity analysis for the Star rope (10 mm), confirming that fiber production is the most impactful phase across all categories. The second-largest contributor is the electricity used during the braiding process, as revealed by the detailed energy consumption breakdown.

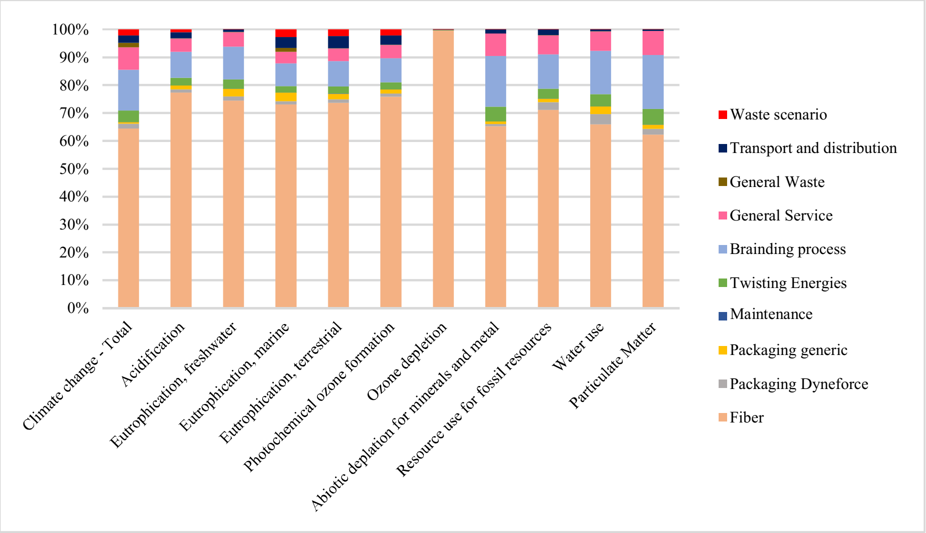

Figure 4. Star gravity analysis

To evaluate the effect of the polymer composition used in the coating of Dyneforce 78, a sensitivity analysis was conducted using a 50/50 mix of polyurethane and epoxy resin. The results showed minimal variation in environmental impact, supporting the validity of the assumed average composition and confirming that this parameter does not affect significantly the overall footprint. The sensitivity analyses showed that variations in results remained below 1%, confirming the robustness of the model. Proxy data use was limited to less than 10%, fully complying with the applicable guidelines. The only critical issue identified during the consistency check concerned the modeling of Dyneema®'s raw material, which required reconstructing the full production pathway from polymer granulates. This modeling was performed carefully, based on scientific literature and relevant patents filed by the fibers' manufacturer, as previously reported.

4. Conclusion

This study assessed the environmental impacts of two nautical ropes, i.e., Dyneforce 78 (UHMWPE) and Star (polyester), through Life Cycle Assessment. Fiber production was identified as the primary contributor to overall impacts in both cases. For Dyneforce 78, energy-intensive coating and heat-setting stages were particularly relevant, while for Star, braiding emerged as the most impactful process. The sensitivity analysis on Dyneforce's polymer composition confirmed that coating formulation has a negligible effect, with variations under 1%. The end-of-life phase was modelled using a realistic disposal scenario: 48.4% landfill, 21% incineration, and 30.6% recycling. The cradle-to-grave framework allowed for the identification of environmental hotspots and potential areas for improvement. Future research should explore material and process optimization to further reduce impacts without compromising rope performance. This work contributes original data to the LCA literature on nautical components and offers practical insights for more sustainable design in the maritime sector.

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References

[1] F. Cucinotta, E. Barberi, and F. Salmeri, A Review on Navigating Sustainable Naval Design: LCA and Innovations in Energy and Fuel Choices, *J. Mar. Sci. Eng. 2024, Vol. 12, Page 520*. **12** (2024) 520. doi:10.3390/JMSE12030520.

[2] F. Del Pero, C.A. Dattilo, A. Giraldi, and M. Delogu, LCA approach for environmental impact assessment within the maritime industry: Re-design case study of yacht's superstructure, *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.* **238** (2024) 153–170. doi:10.1177/14750902231173470/SUPPL_FILE/SJ-DOCX-1-PIM-10.1177_14750902231173470.DOCX.

[3] A. Mio, M. Fermeglia, and C. Favi, A critical review and normalization of the life cycle assessment outcomes in the naval sector. Articles description, *J. Clean. Prod.* **370** (2022) 133476. doi:10.1016/j.jclepro.2022.133476.

[4] A. Mio, M. Fermeglia, and C. Favi, A critical review and normalization of the life cycle assessment outcomes in the naval sector. Bibliometric analysis and characteristics of the studies, *J. Clean. Prod.* **371** (2022) 133268. doi:10.1016/j.jclepro.2022.133268.

[5] M.S. Otero, T. Garnica, S. Montilla, M. Conde, and J.A. Tenorio, EPD as LCA Quality Input Data. A Critical Analysis, (2023). doi:10.20944/PREPRINTS202311.0010.V1.

[6] Armare Ropes Srl, (n.d.). https://www.armareropes.com/en/.

[7] B. Busetto, A. Bordignon, A. Bortoluzzi, S. Milanesi, A. Paduano, and A. Mio, Life Cycle Assessment in the Naval Sector: Between Certification and New Materials, *Prog. Mar. Sci. Technol.* **6** (2022) 564–571. doi:10.3233/PMST220067.

[8] Quotasette s.r.l;, Mapping LCA, Northern Light S.r.l., MolBNL (University of Trieste – Department of Engineering and Architecture), Water Revolution Foundation, MICAD;, Naval Design & Consulting;, and European Boating Industry (EBI), PCR: Yachts, small crafts, other vessels, and components thereof, International EPD System, 2023.

[9] International Standard Organization, ISO 14040 series -Environmental Management – Life Cycle Assessment – Principles and Framework, Geneva, Switzerland, 2006.

[10] The International Standards Organisation, ISO 14044 Environmental

management — Life cycle assessment — Requirements and guidelines, 2006.
[11] International EPD System, General Programme Instructions for the International EPD® System. Version 4.0, (2021) 80. http://www.environdec.com/.
[12] Y. Wang, X. Wang, J. Fu, J. Yu, Y. Wang, and Z. Hu, Enhanced tensile properties of ultra-high molecular weight polyethylene fibers by solubility improvement with mixed solvents, *J. Appl. Polym. Sci.* **140** (2023) e53715. doi:10.1002/APP.53715.
[13] M. SIMMELINK, Joseph, Arnold, Paul, and M. STEEMAN, Paulus, Antonius, FIBERS OF UHMWPE AND A PROCESS FOR PRODUCING THEREOF, EP 2 195 476 B1, 2010.
[14] UNEP - UN Environment Programme, Global Waste Management Outlook 2024, 2024. https://www.unep.org/resources/global-waste-management-outlook-2024 (accessed April 14, 2025).