enespa®
green technologies

Novel Metrics to measure the Contribution of Plastic-to-Oil Recycling

Innovation Cheque 69117.1 Inno-EE

August 2024

Innovation cheque supported by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

Content Outline

enespa® green technologies

enespa® green technologies

A. Executive Summary

A. Executive Summary

enespa® green technologies

The Material Plastic:
Background and Issues

- Plastic is a key-material for the economic development and growth
  ➔ global production volume of plastic amounts nowadays to almost 500mn tons p.y. (at 2000: ca.200tons; 1970: 35tons)[1]
- Alongside with the conomic benefits arise ecological, social and economic challenges from plastics such as:

  a) Ecological: water and soil pollution, harm to vital biodiversity, GHG emissions

  b) Social: harm to health and life expectation, reduction living quality, constraint in living environment

  c) Cconomic: costs for mismanaged plastic waste, GHG emissions and negative impact on health around CHF 3tn p.y.[2]

Challenges:
Maturity level in Plastic Recycling issues

- So far, only 10% of global plastic waste is recycled due to challenges in collection of plastic waste, contamination of plastic waste, structure of plastic waste, lack in education
- Furthermore, several technological recycling methods not sufficiently matured and reasonable applied
- **In addition, resilient and measurable metrics comprising ecological, social and economic aspects have not be existent for innovative recycling technologies such as plastic-to-oil conversion**

Study Results:
Developed Metrics, Index Set-up, Effects Illustration

- Study focus on detecting and deloping metrics for plastic-to-oil indsutry

  a) 75 ESG metrics with relevance for plastic-to-oil industry scrutinized

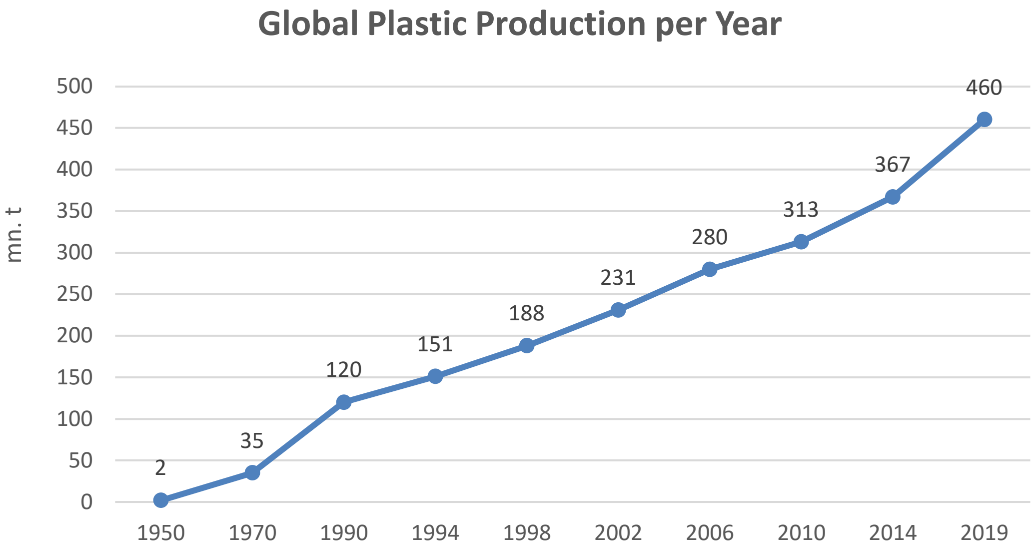
  b) 10 crucial metrics developed with specific relvance for plastic-to-oil industry
- New Eco-Perfomance Index elaborated
- Effects on Economy, Society and Environment illustrated resulting from plastic-to-oil recycling

Sources:
1 Statista, 2024: Weltweite und europäische Kunststoffproduktion in den Jahren von 1950 bis 2021; https://de.statista.com/statistik/daten/studie/167099/umfrage/weltproduktion-von-kunststoff-seit-1950/ OECD, 2019: Plastic use in 2019, https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en; Geyer, R. et al., 2017: Production, use and fate of all plastic ever made, https://doi.org/10.1126/sciadv.1700782
2 WWF/Dalberg, 2021: Plastics: The costs to society, the environment and the economy, https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Plastik/WWF-PCSEE-Report-Plastics-the-Costs-to-Society-the-Environment-and-the-Economy.pdf

enespa®
green technologies

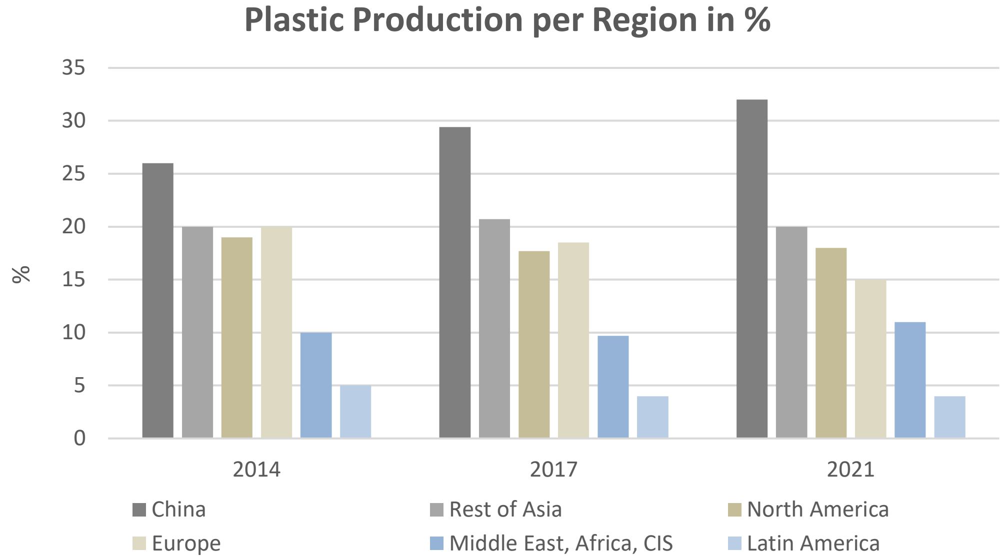
B. An Overview about Plastic – General Data and Facts

B. An Overview about Plastic - Production



CAGR since 1950: 8.2%

Growth last 30 years: 283%



China up by 6%-points

Europe down by 5%-points

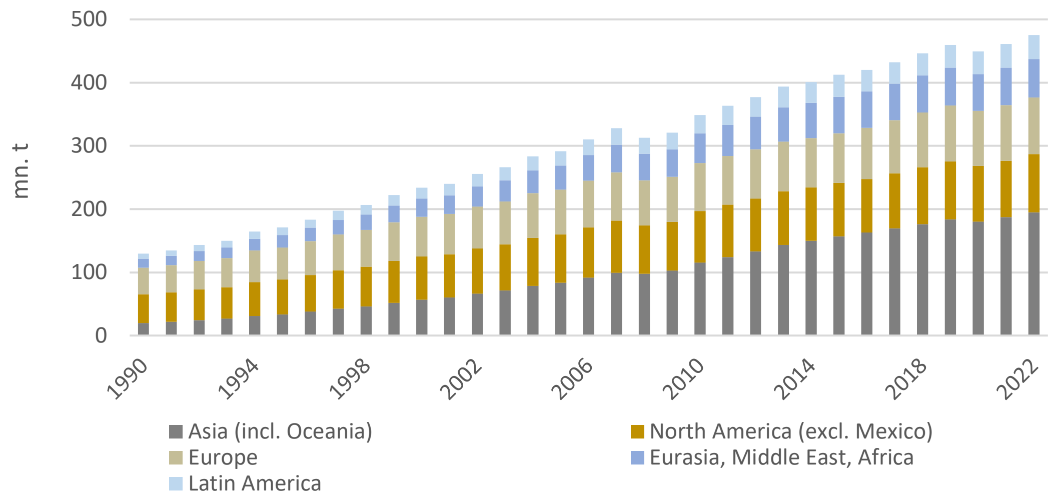
Development Plastic Production

- Total cumulated plastic production amounts to 8.3bn metric tons since 1950; current yearly plastic production (resin & fibers) heads towards 500mn t/year.[1]
- In 2021 ca. 90% of plastic production comes from fossil fuels[2], ca. 9% from recycled plastic and 1% from bio materials.
- Plastic production and usage has out outreached most other materials (due to global construction activities mass amount of concrete and steel higher than plastic).[3]
- Strong correlation between economic development and plastic production & usage indicating a high relevance of plastic for the economic prosperity. [5]
- Asia and there in specific China account since 2021 for more than 5o% of global plastic production due to decreasing competitiveness of European and American polymere industry. [1]
- According to OECD the amount of produced plastic in metric tons will ca. threefold until 2060 despite technological advancements in plastic production. [6]

Sources:
[1] Ritchie et al. (OECD), 2022: Global Plastics Production, https://ourworldindata.org/plastic-pollution; PlasticsEurope (PEMRG), 2021: Plastics – The facts 2021, https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf ; Fogh et al., 2020: Plastics, the circular economy and Europe's environment — A priority for action, https://www.eea.europa.eu/publications/plastics-the-circular-economy-and
[2] Fossil fuels comprise oil, natural gas, salt, cellulose and coal)
[3] Geyer, R. et al., 2017: Production, use and fate of all plastic ever made, https://doi.org/10.1126/sciadv.1700782 ; OECD, 2023: OECD Environmental Performance Reviews, 10.1126/sciadv.1700782
[5] Cordier et al., 2021: Plastic pollution and economic growth: The influence of corruption and lack of education, https://doi.org/10.1016/j.ecolecon.2020.106930
[6] OECD, 2023: Plastics use projections to 2060, https://www.oecd-ilibrary.org/sites/aa1edf33-en/1/3/2/2/index.html?itemId=/content/publication/aa1edf33-en&_csp_=ca738cf5d4f327be3b6fec4af9ce5d12&itemIGO=oecd&itemContentType=book

B. An Overview about Plastic – Plastic Usage

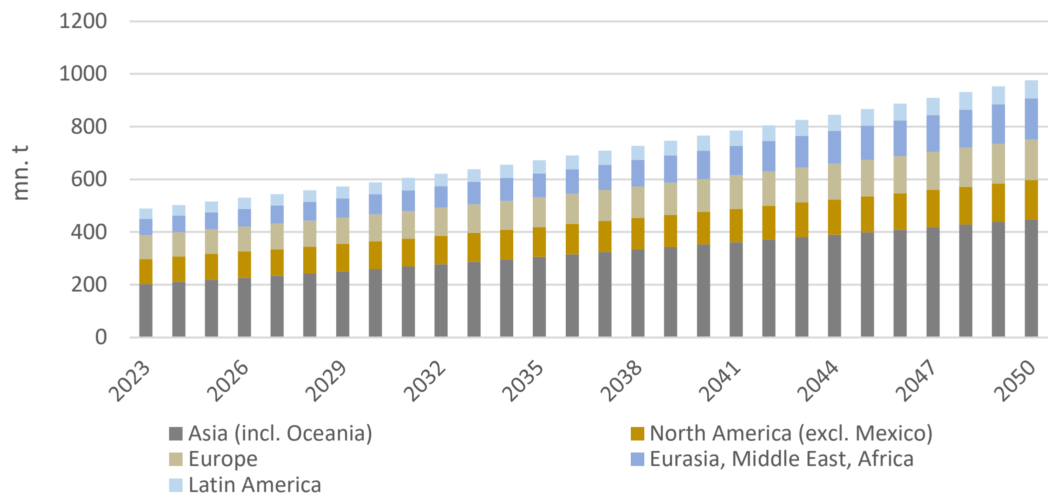
Plastic Usage by Region



Unitl 2005 Europe & North America >50%

Asia's growth rate highest in last 30y.: +885%

Plastic Usage by Region Forecast



Usage increase mainly driven by Emerging Countries

Asia: +144%
Eurasia: +161%
Latin A.: +91%

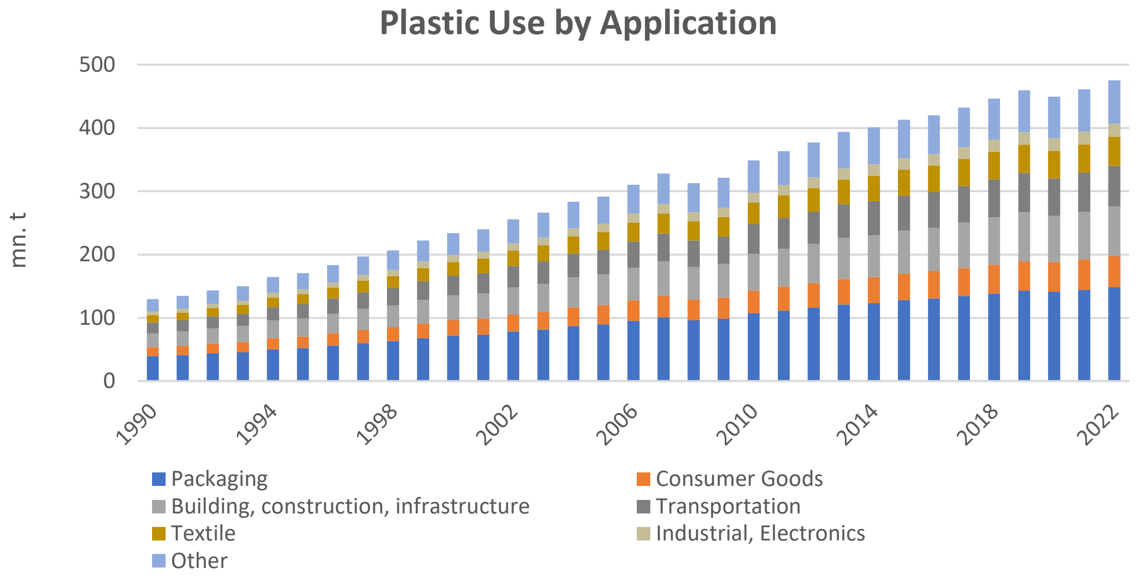
Development Plastic Usage by Region

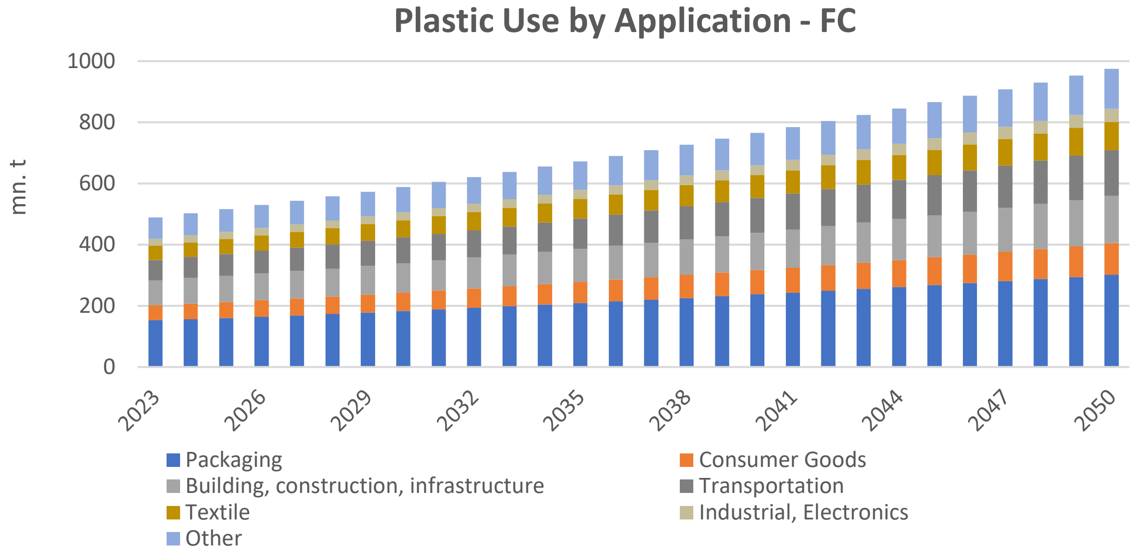
- Over all regions the plastic usage has almost quadrupled since 1990 even when the population only grew about 50%. Industrialized countries dominated plastic usage until beginning in the 20th century.[1]
- Since the fast growth of emerging countries contribute now intensively to the additional usage of plastic.
- Particularly emerging countries like China, India and Indonesia have become the main responsible growth in plastic usage due to their strong economic growth and the growing population in most of these countries. [2]
- Subsequently, projected increase in plastic usage over the next 25 years is mainly driven by Asia, whereas the amount of used plastic in Western countries is projected on lower levels.[3]

Sources:
1 Statista, 2024: Weltweite und europäische Kunststoffproduktion in den Jahren von 1950 bis 2021; https://de.statista.com/statistik/daten/studie/167099/umfrage/weltproduktion-von-kunststoff-seit-1950/
OECD, 2019: Plastic use in 2019, https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en
2 Carbernard et al., 2015: Growing environmental footprint of plastics driven by coal combustion, https://www.nature.com/articles/s41893-021-00807-2
3 OECD, 2019: Library on Global Plastic Outlook, https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en

B. An Overview about Plastic – Plastic Use by Application

enespa® green technologies





240-290%% increase at all appl. in last 30 y.

Packaging & Construction the main appli.

Steady increase in all applications predicted

Transport a bit stronger due to global trade: +201%

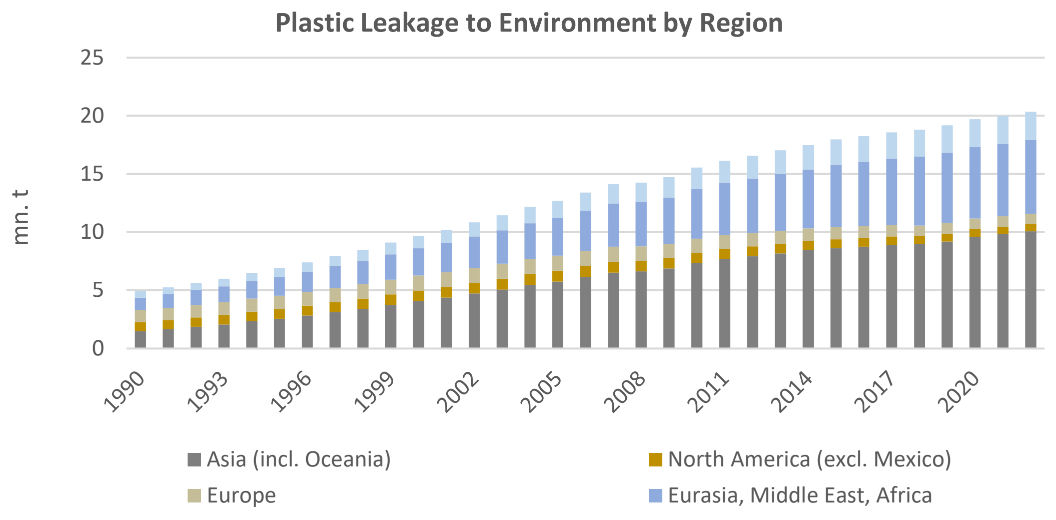
Development Plastic Use by Application by Region

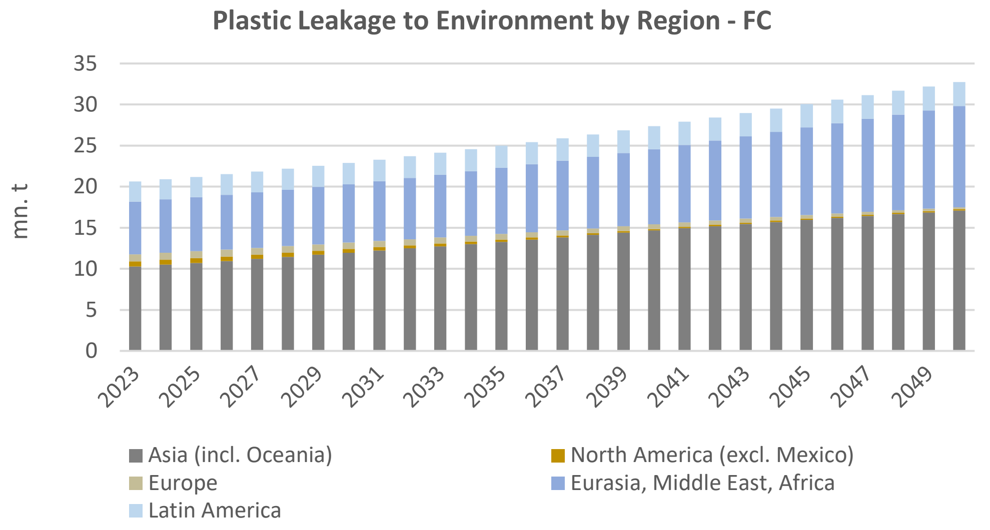
- Plastic is the most used material for packaging even more used than paper and cardboard. [1]
- Plastic is a cheap and easily to adapt material with the advantage to match the respective requirements for its application, e.g. the application ranges from a very soft, bendable, but still protective material like foils to a highly rigid and stable materials like furniture in public spaces, food containers or even constructions materials.[2]
- Without plastics, several material developments and innovations would not have taken place. Plastic is also considered of being a crucial element for the economic development and the increase in economic wealth.[3]
- But the challenge of the negative impact plastic pollution to environment and society to be addressed to keep up the economic benefits.[4]
- According to current status of technology (mechanical and chemical recycling) 78% of plastic waste could be recycled until 2040.[5]

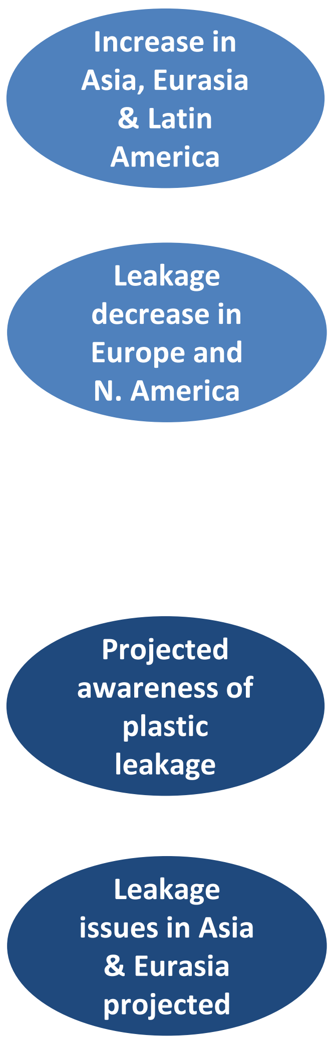
Sources:
[1] Jambeck et al., 2015: Plastic waste inputs from land into the ocean, DOI: 10.1126/science.1260352
[2] Zheng/Suh 2019: Strategies to reduce the global carbon footprint of plastics, https://www.nature.com/articles/s41558-019-0459-z ; Andradi/Neal, 2009: Applications and societal benefits of plastics, 10.1098/rstb.2008.0304
[3] PlasticsEurope, 2021: The Compelling Facts About Plastics. https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf
[4] Zhang et al., 2022: From trash to treasure: Chemical recycling and upcycling of commodity plastic waste to fuels, high-valued chemicals and advanced materials, https://doi.org/10.1016/j.jechem.2021.12.052 ; Chamas et al., 2020: Degradation Rates of Plastics in the Environment, https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635 Vollmer et al., 2020: Beyond Mechanical Recycling: Giving New Life to Plastic Waste, doi.org/10.1002/anie.201915651
[5] Lau et al., 2020: PLASTIC POLLUTION: Evaluating scenarios toward zero plastic pollution, https://www.science.org/doi/pdf/10.1126/science.aba9475

B. An Overview about Plastic – Uncontrolled env. leakage

enespa® green technologies





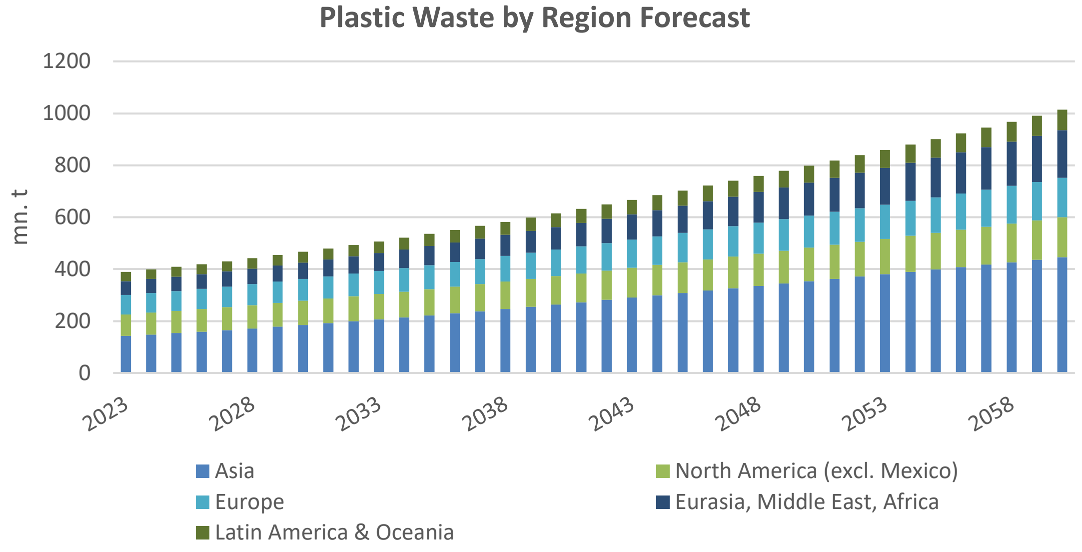


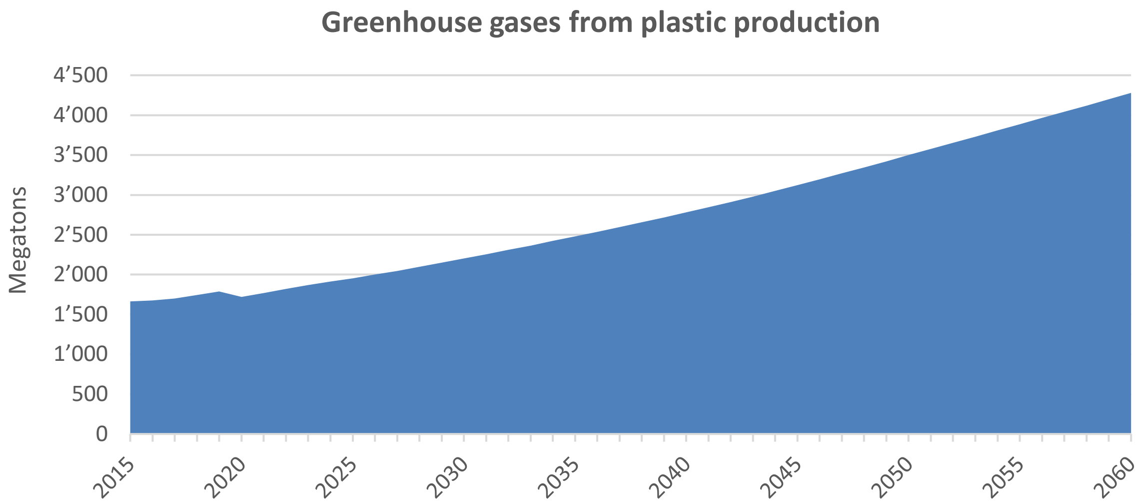
Development of Plastic Leakage[1]

- *Asia*
  Since 1990: +580%
  Forecast until 2050: +70%
- *North America*
  Since 1990: -18%;
  Forecast until 2050: -73%
- *Europe*
  Since 1990: -14%;
  Forecast until 2050: -70%
- *Eurasia, ME, Africa*
  Since 1990: +476%;
  Forecast until 2050: +92%
- *Latin America:*
  Since 1990: +347%
  Forecast until 2050: +20%
- Forecast shows challenge to either reduce the plastic usage or to integrate it in a sustainable recycling circle (as many plastic recycling methods only convert plastic into low quality plastic the issue of plastic waste impact to environment and society is not resolved but postponed)

Sources:
[1] OECD, 2019: Library on Global Plastic Outlook, 2019, https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en

B. An Overview about Plastic – Waste and GHG emissions





Development Plastic Waste

- Global emitted plastic waste has increased from 156mn tons in 2000 to currently ca 400mn tons. Until 2016 OECD countries main plastic responsible; since 2017 Non-OECD surpassed OECD countries and account now for 53% of total waste.[1]
- OECD data predicts plastic waste to suprass the threshold of 1bn tons p.y. by 2060.[1]
- Plastic counts for one of the biggest waste pollution issues:
  - Hazard to biodiversity including all kinds if animals affected by plastic pollution
  - Microplastic found all around the globe with harmful impact on spring water, food, soil
  - Biosphere constraints due to plastic waste.[3]
- Plastic waste trade flows: Until 2017 developed countries exported twice as much plastic waste as they imported; due to increase in recycling rates plastic ex- and imports level off in industrialized countries, which also indicates the economic attractiveness of plastic recycling.[4]

Development GHG

- Plastics contribute 3.3% (1.8bn tons p.y.) to global GHG emissions. Ca. 90% of the emissions result from plastic production. [5]
- Increase in carbon emissions correlates with surge in plastic production
- Bio-based plastics combined with smart recycling such as turning plastic back into oil could enable carbon neutrality or at least a significant reduction (ca. 83%). [6]

Sources:
[1] OECD, 2029: Plastic waste in 2019, https://doi.org/10.1787/a92f5ea3-en
[2] OECD, 2023: Plastic waste by end-of-life fate and region – projections. https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en
[3] Aviso et al., 2023: Optimizing plastics recycling networks, https://doi.org/10.1016/j.clet.2023.100632;
[4] Brown et al., 2023: Monitoring trade in plastic, waste and scrap, https://one.oecd.org/document/ENV/WKP(2024)3/en/pdf
[5] OECD, 2022: Our World in Data, https://ourworldindata.org/
[6] Sun et al., 2023: Biobased plastic: A plausible solution toward carbon neutrality in plastic industry?, https://doi.org/10.1016/j.jhazmat.2022.129037

C. Plastic Life Cycle and Recycling Methods

C. Plastic Types, Applications & Recyclability

enespa® green technologies

Types of Plastic according to its resin codes[1]

1 PET	2 HDPE	3 PVC	4 LDPE	5 PP	6 PS	7 OTHER
Softdrink and water bottles	Containers for milk, shampoos and detergents	Pipes and tiles	Plastic grocery bags	Plastic bottle caps, lunch boxes	Plastic cutlery and packing foam	Baby bottles, CDs and DVDs

Further plastic applications[2]

- Saving energy for transporation by being lightweight
- Production of plastic being cheap
- Due to the strength of plastic only little material being needed
- Allowing disposable products useful for example medical equipment
- Protecting food and beverages from outside and preventing food waste

Recyclability or plastic types[3]

- Mechanical Recycling:
  - Generally recyable: Plastics with the resin code 1 and 2
  - Challenging to recycle: Plastics with the resin codes 4-7
  - Not recycble: Plastics with the code 3
- Chemical Recycling:
  - Most materials should be recyclable
  - Current limiting factors: Efficient applicability, energy efficiency, technological solution in maintaing output quality, feedstock prices, volume availability
  - PET specific: Usually contains 30% oxygen, therefore ineligible for thermolysis

Sources:

1 Seaman, 2020: Plastic by the Numbers, https://learn.eartheasy.com/articles/plastics-by-the-numbers/

2 Andrady/Neal, 2009: Applications and societal benefits of plastics, doi: 10.1098/rstb.2008.0304

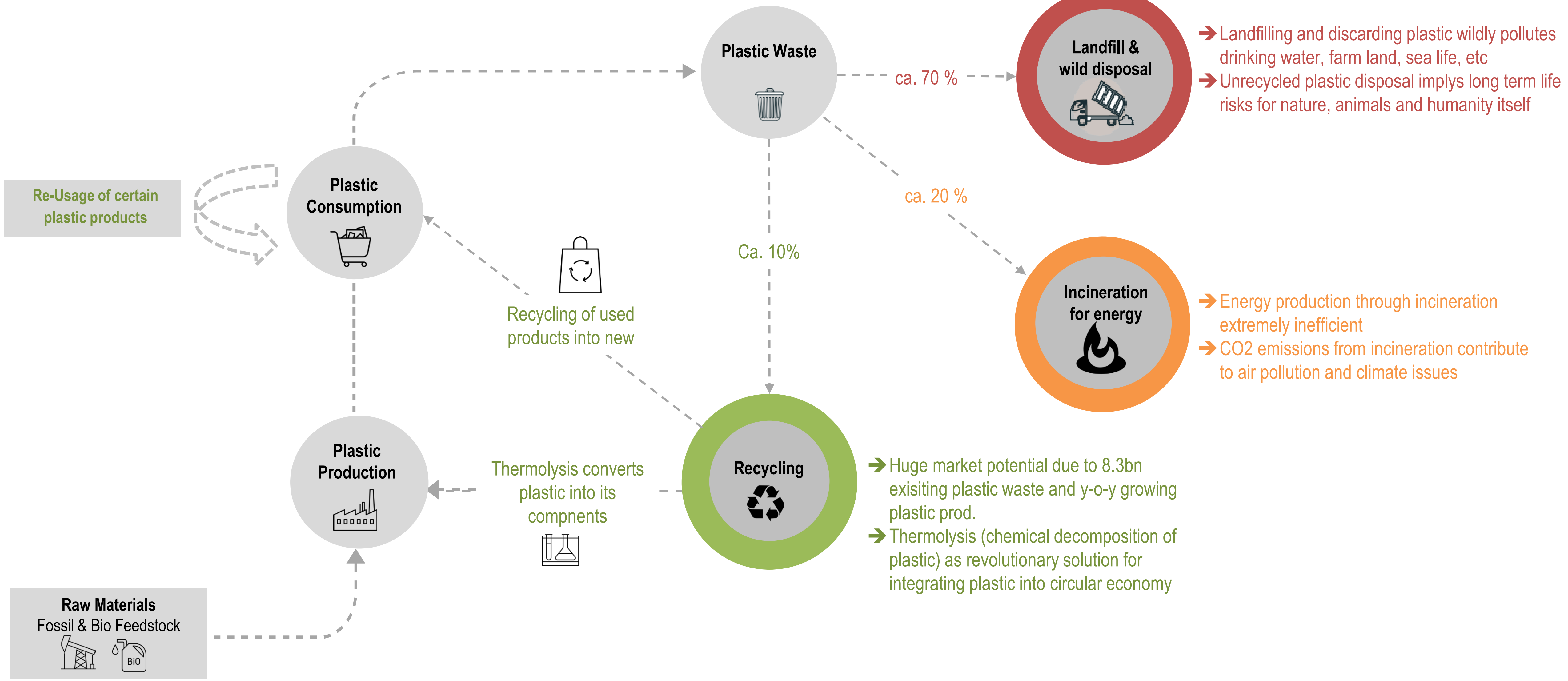
3 Lu et al., 2023: Chemical recycling technologies for PVC waste and PVC-containing plastic waste: A review, https://doi.org/10.1016/j.wasman.2023.05.012

Zhang et al., 2022: From trash to treasure: chemical recycling and upcycling of commodity plastic waste to fuels, high-valued chemicals and advanced materials, https://doi.org/10.1016/j.jechem.2021.12.052

Kumar et al., 2023: Mechanical, chemical, and bio-recycling of biodegradable plastics: A review. https://doi.org/10.1016/j.scitotenv.2023.163446

C. Plastic Life Cycle and Recycling Methods

The global Life Cycle of Plastic and its potentials and risks from plastic waste[1,2]



Sources:

[1] Own Illustration based on: Geyer et al., Jiao et al., 2024: A critical review on plastic waste life cycle assessment and management: Challenges, research gaps, and future perspectives, https://www.sciencedirect.com/science/article/pii/S0147651324000174, Bachmann et al. 2023: Towards circular plastics within planetary boundaries, https://doi.org/10.1038/s41893-022-01054-9 ; OECD, 2022: Annual plastic waste by disposal method, World, 2000 to 2019, https://ourworldindata.org/grapher/plastic-fate 2017: Production, use, and fate of all plastics ever made, https://www.science.org/doi/10.1126/sciadv.1700782; Schneider/Ragosing, 2015: Recycling and incineration, contradiction or coexistence?, https://journals.sagepub.com/doi/10.1177/0734242X15593421:

2 The recycling rates vary between continents, e.g. Europe^s recycling rate ca. amounts to 27%, Plastics Europe, 2024: The circular economy for plastics – a European analysis, https://plasticseurope.org/wp-content/uploads/2024/03/CEreport_fullreport_2024_light-1.pdf

C. Plastic waste processing [1]

A) Incineration:

- Incineration is the method of burning waste into oxygen and to produce energy
- High capital expenditure required for respective facilities
- After incineration the waste is composed of ash, different chemicals and hydrochlorid acid.
- Since some of the plastic waste is resistant to oxygen heating, not all plastic waste can be incinerated.
- Risk: Incineration of not well sorted plastics can entail hazardous incidents as e.g. explosions.

B) Landfill:

- Landfill refers to store plastic waste on one specific place .
- The goal is to have a certain area for plastic waste to protect the environment in other areas from the negative impacts of plastic waste
- There must be many precautions taken to avoid secondary side effects like groundwater contaminations.
- Landfill plastic waste takes up to 100 years to degrade; during decomposition GHG are released
- It is a cost-effective method for waste management
- Wild Disposal refers to uncontrolled littering of plastic waste causing the maximum negative impact for environment, animals and society

C) Recycling:

- Recycling refers to collection plastic waste and converting it into raw material to be used again as plastic or even oil
- The recycling is carried out either mechanically or chemically
- Mechanical recycling generally applied for rather simple and lower quality products
- Chemical recycling can convert plastic waste into its original components like oil
- Big breakthrough in 2024: On August 28th, scientists at ETH released an article about the formula and process how to effectively and efficiently recycle plastic

Sources:
[1] Jiao et al., 2024: A critical review on plastic waste life cycle assessment and management: Challenges, research gaps, and future perspectives, https://doi.org/10.1016/j.ecoenv.2024.115942; Evode et al., 2021: Plastic waste and its management strategies for environmental sustainability, https://doi.org/10.1016/j.cscee.2021.100142; European Environment Agency, 2020: Plastics, the circular economy and Europe's environment, https://www.eea.europa.eu/publications/plastics-the-circular-economy-and ;
2 Jaydev et al., 2024: Assessment of transport phenomena in catalyst effectiveness for chemical polyolefin recycling, https://www.nature.com/articles/s44286-024-00108-3

C. Methods of Plastic Recycling

A) Plastic recycling into the same product

Plastic waste is difficult to recycle into the same end-product since packaging often requires different materials aswell as well different plastic types. The polymer grades in the waste needs to be similair for primary mechanical recycling. Since PET are mainly made of similar grades of plastic, clean PET Bottles are often recycled into the same product. Recycling into the same product creates a closed loop where no virgin resin is needed. This eliminates a big part of the negative impacts resulting from the extraction of oil and gas as long as the recycling process is energy efficient.[1]

B) Plastic recycling into other products

If the waste doesn't contain the same or similar plastic grades, the secondary recyling method might be applied. Secondary plastic recycling refers to downcyling of the plastic thereby trying to split the different grades. To carry out the process plastic needs to be clean and not contaminated.[2] The received components in this process can't be fully used to create the same endproduct as before. Thus, Secondary mechanical recylcling therefore can't fully contribute to a circular economy although it prevents waste from going to the landfill.[3]

C) Plastic recycling into its original components

Plastic considered difficult to recycle can often be used for Pyrolisis (chemical recycling). Pyrolisis can even handle unclean plastic waste. Plastic with about 20% contamination from food remnants can still be recycled through that process. However, Pyrolisis procedure generally requires high amounts of processed feedstock to cover the high capital investment costs and to finally become profitable. To this issues is flanked the the technological challenge to sustain a high quality level over the high quantities of processed feedstock.[4]

Plastic Products Recycling Process[5]

[1] Hopewell et al., 2009: Plastics recycling: challenges and opportunities, https://royalsocietypublishing.org/doi/10.1098/rstb.2008.0311
[2] Ignatyev et al., 2014: Recycling of polymers: a review Ignatyev, https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/cssc.201300898
[3] Schyns/Shaver, 2020: Mechanical Recycling of Packaging Plastics: A Review, https://onlinelibrary.wiley.com/doi/10.1002/marc.202000415
[4] Kulas et al., 2023: Economic and environmental analysis of plastics pyrolysis after secondary sortation of mixed plastic waste, https://www.sciencedirect.com/science/article/abs/pii/S0959652622051162
[5] Association of Plastic Recyclers, 2022: The Plastic Recycling Process, https://plasticsrecycling.org/the-plastic-recycling-process

enespa green technologies

D. Plastic-to-Oil Metrics - Research Results Part One

D. Applied Methodology and Accomplished Results

Selection Methodology

ESG Metrics: As base for the analysis acknowledged ESG metrics (such as MSCI ESG metrics) were used.

Plastic-to-Oil Metrics Screening: Detailed screening whether ESG metrics with reference to Plastic-to-Oil industry are applied.

➔ *Result: No general or specific Plastic-to-Oil Metrics so far*

Plastic-to-Oil Metrics Development: A) Comprehensive analysis of existing ESG metrics and examination of its applicability to Plastic-to-Oil industry. **B)** In addition, analysis for new and not yet existing metrics designed for the plastic-to-oil industry according to ESG logic.

Used Database: LSEG Refinitiv

Accomplished Analysis Results

ESG-Metrics for Plastic-to-Oil Industry: Out of 279 ESG metrics commonly used for the oil and recycling industry, ***75 ESG metrics*** were detected as applicable for the Plastic-to-Oil industry (see attached list of ESG - PtO Metrics for details).

New Metrics: With regards to the specifics of the Plastic-to-Oil Industry ***10 Metrics*** were developed for the Plastic-to-Oil Industry.

Benchmarking Index: Set-up of an Eco-Performance Index out of Metrics

D. Plastic to Oil KPIs 1/5

Volume of Plastic Recycled

Description: Total weight of plastic waste processed and transformed into oil.

Calculation: Obtained by taking the sum of all plastic waste inputs.

Data Sources: Operational data, waste input logs.

Relevance for environmental regulation: Demonstrates commitment to waste reduction and recycling, aligning with regulations focused on waste management and recycling quotas, such as the EU's Waste Framework Directive and similar regulations in other jurisdictions that mandate recycling targets.

Metric: Total kilograms or tons of plastic waste processed into oil annually.

Source: US EPA, 2024: Plastics: Material-Specific Data, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

GHG Emissions Reduction

Description: Reduction in greenhouse gas emissions compared to traditional disposal.

Calculation: Difference in GHG emissions between recycling and baseline scenarios.

Data Sources: Emissions testing, industry-standard emission factors.

Relevance for environmental regulation: Addresses climate change regulations, such as those under the Paris Agreement, by demonstrating reductions in greenhouse gas emissions. It can also contribute to compliance with national GHG reduction targets and carbon trading schemes, like the EU Emissions Trading System (EU ETS).

Metric: Tons of CO_2 equivalent (CO_2e) saved annually by recycling plastics compared to traditional disposal methods.

Source: Gracidas et. al, 2023: Life-cycle analysis of recycling of post-use plastic to plastic via pyrolysis, https://doi.org/10.1016/j.jclepro.2023.138867

D. Plastic to Oil KPIs 2/5

Energy Consumption

Description: Energy used per unit of oil produced.

Calculation: Total energy consumed divided by the volume of oil produced.

Data Sources: Energy usage records, production logs.

Relevance for environmental regulation: Helps in meeting energy efficiency standards and regulations, such as the EU Energy Efficiency Directive (EED), by demonstrating efficient energy use in operations. This KPI can also align with global energy management standards like ISO 50001.

Metric: Kilowatt-hours (kWh) of energy used per kilogram or liter of oil produced.

Source: Shan et. al, 2023: Environmental Impact of Plastic Recycling in Terms of Energy Consumption: A Comparison of Japan's Mechanical and Chemical Recycling Technologies, https://doi.org/10.3390/en16052199

Lifecycle Analysis

Description: Environmental impact of the recycled oil considering the full lifecycle.

Calculation: Comprehensive lifecycle analysis.

Data Sources: Lifecycle assessment studies, industry data.

Relevance for environmental regulation: Supports compliance with environmental product declarations (EPD) and regulations requiring detailed environmental impact assessments of products. This KPI can be instrumental in meeting requirements of the EU Ecolabel and similar schemes that assess the environmental footprint of products throughout their lifecycle.

Metric:

- *Global Warming Potential (GWP):* Kilograms of CO2 equivalent per kilogram or liter of oil produced, covering all lifecycle stages.
- *Water Footprint:* Total liters of water consumed, evaporated, or polluted per kilogram or liter of oil produced throughout its lifecycle.

Source: Coban/Ekici/Karakoc, T.H., 2024: Life Cycle Assessment: A Brief Definition and Overview
https://rdcu.be/dMBI6

D. Plastic to Oil KPIs 3/5

Waste Management Efficiency

Description: Efficiency in managing by-products and wastes.

Calculation: Percentage of waste recycled, reused, or safely disposed of.

Data Sources: Waste management logs, environmental reports.

Relevance for environmental regulation: Supports compliance with waste management regulations by demonstrating efficient waste processing and disposal. This KPI can help meet the requirements of regulations that focus on minimizing landfill use and promoting waste hierarchy practices, such as the EU Landfill Directive.

Metric: Percentage of by-product and waste materials (from the recycling process) that are reused, recycled, or safely disposed of.

Source: Oke/Kruijsen, 2016: The Importance of Specific Recycling Information in Designing a Waste Management Scheme, https://doi.org/10.3390/recycling1020271

Water Consumption

Description: Water used in the recycling process.

Calculation: Total water used divided by the volume of oil produced.

Data Sources: Water usage meters, process monitoring systems.

Relevance for environmental regulation: Aligns with water management regulations and standards, contributing to compliance with local water use and efficiency regulations, as well as broader initiatives like the EU Water Framework Directive, which aims to protect and conserve water resources.

Metric: Liters of water used per kilogram, or liter of oil produced.

Source: Alassali et.al, 2021: Towards Higher Quality of Recycled Plastics: Limitations from the Material's Perspective, https://doi.org/10.3390/su132313266

D. Plastic to Oil KPIs 4/5

enespa green technologies

Type of Plastic Recycled

Description: Types of plastics recycled, showcasing capability.

Calculation: Categorization and percentage breakdown.

Data Sources: Waste input logs, recycling process data.

Relevance for environmental regulation: Supports adherence to specific regulations concerning the recycling of certain types of plastics, which may have different environmental impacts and recycling challenges. This KPI can help in complying with directives that require detailed reporting on the types of waste processed, such as the EU Waste Framework Directive.

Metric: Percentage breakdown of recycled plastic types (e.g., PET, HDPE, LDPE) against total plastic input.

Source: Joseph et.al, 2024: Polyethylene terephthalate (PET) recycling: A review, https://doi.org/10.1016/j.cscee.2024.100673

Resource Conservation

Description: Impact on conserving natural resources through recycling.

Calculation: Estimated resources saved by recycling.

Data Sources: Industry equivalency rates, operational data.

Relevance for environmental regulation: By showing how recycling activities conserve natural resources, this KPI supports compliance with regulations aimed at resource efficiency and sustainable material management, contributing to circular economy goals outlined in policies like the EU Circular Economy Action Plan.

Metric:

- *Virgin material savings:* Estimated kilograms or tons of virgin resources (e.g., crude oil) saved through the recycling process annually.
- *Energy savings:* Kilowatt-hours (kWh) saved by using recycled plastics instead of producing new plastic or oil from virgin resources.

Source: Gabisa et.al, 2023: Recycling of Plastics as a Strategy to Reduce Life Cycle GHG Emission, Microplastics and Resource Depletion, https://doi.org/10.3390/su151511529

D. Plastic to Oil KPIs 5/5

enespa® green technologies

Biodiversity Impact

Description: Operations' impact on local biodiversity.

Calculation: Qualitative assessments or biodiversity indexes.

Data Sources: Environmental impact assessments, biodiversity studies.

Relevance for environmental regulation: Aligns with biodiversity protection and conservation regulations, such as those under the Convention on Biological Diversity (CBD). It can help demonstrate compliance with environmental impact assessment requirements and habitat protection regulations.

Metric:

- Qualitative assessments (e.g., Environmental Impact Assessments (EIA)) of operational impacts on local habitats and species.
- Number of biodiversity enhancement projects initiated or supported.

Source: Fauna/Flora, 2021: Marine Plastics: A threat to biodiversity and conservation efforts, *https://www.fauna-flora.org/wp-content/uploads/2023/12/2023DEC11_Fauna-flora-Biodiversity-Briefing-Final-rev.pdf*

Pollution Control

Description: Efforts to control pollution emissions.

Calculation: Reduction in pollutant levels or compliance rates.

Data Sources: Emissions testing, environmental compliance reports.

Relevance for environmental regulation: Ensures compliance with pollution control regulations, such as the Clean Air Act, Clean Water Act, and other local and international regulations aimed at minimizing emissions and effluents from industrial activities.

Metric:

- Reduction in pollutant emissions (e.g., NOx, SOx, particulate matter) measured in kilograms or tons per year.
- Compliance rate with local and international emission standards (percentage of time in compliance).

Source: US EPA, 2024: Clean Air Act & Clean Water Act
https://www.epa.gov/clean-air-act-overview
https://www.epa.gov/laws-regulations/summary-clean-water-act

E. Benchmarking Framework: Eco Performance Index – Research Results Part Two

E. Benchmarking Framework: The EcoPeformance Index

enespa®
green technologies

EcoPerformance Index (EPI)

IDEA: A self-developed scoring index that assigns points to each KPI based on a standardized performance measurement. This systematic approach will aggregate (sum up) the standardized scores allocated for each individual KPI to calculate an overall index. As such, the approach will enable the benchmarking of different players in the plastic to oil business.

Scoring Framework: Each KPI will be scored on a scale of 0 to 10, where 0 indicates poor performance and 10 indicates excellent performance. The scores for each KPI will be weighted based on their importance. For simplicity, we'll assume equal weighting for all KPIs, but this can be adjusted based on organizational priorities.

Steps to Calculate the Index:

1. **Standardize the KPIs:** Normalize the data for each KPI to ensure comparability.
2. **Assign Scores:** Develop a scoring rubric for each KPI.
3. **Apply Weights:** Multiply the scores by their respective weights.
4. **Calculate the Index:** Sum the weighted scores to get the overall index.

E. Index Calculation Process

Step 1:
Standardize the KPIs

Convert each KPI value to a standardized score (e.g., using a min-max normalization process)

$$\text{Standardized Score} = \frac{\text{Actual Value} - \text{Minimum Value}}{\text{Maximum Value} - \text{Minimum Value}} \times 10$$

Step 2:
Assign Scores

Develop a rubric to translate standardized scores into performance scores (0-10).

Example: Energy Consumption (kWh per liter of oil)

- ***Above 2.5 kWh per liter:** 0 points*
- ***2.1 - 2.5 kWh per liter:** 2 points*
- ***1.6 - 2.0 kWh per liter:** 4 points*
- ***1.1 - 1.5 kWh per liter:** 6 points*
- ***0.6 - 1.0 kWh per liter:** 8 points*
- ***Below 0.6 kWh per liter:** 10 points*

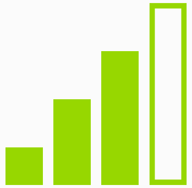
Step 3:
Apply Weights

Convert each KPI value to a standardized score (e.g., using a min-max normalization process)

$$\text{Weight} = \frac{1}{\text{Total Number of KPIs}}$$

Step 4:
Calculate Index

Sum the weighted scores for each KPI to get the overall index.



XX / Max Score of 10

E. Index Calculation Process: Example

enespa® green technologies

Step 1: Standardize the KPIs

Assume the following actual values for each KPI:

1. ***Volume of Plastic Recycled:*** *3,500 tons*
2. ***GHG Emissions Reduction:*** *10,000 tons CO2e*
3. ***Energy Consumption:*** *1.5 kWh per liter of oil*
4. ***Lifecycle Analysis (GWP):*** *2 kg CO2e per liter of oil*
5. ***Waste Management Efficiency:*** *85%*
6. ***Water Consumption:*** *5 liters per liter of oil*
7. ***Type of Plastic Recycled:*** *40% LDPE, 40% HDPE, 10% PS, 10% PP*
8. ***Resource Conservation:*** *4,000 tons of virgin material saved*
9. ***Biodiversity Impact:*** *3 projects initiated*
10. ***Pollution Control:*** *95% compliance rate*

Step 2: Normalized Scores

Assume the following actual values for each KPI:

1. ***Volume of Plastic Recycled: 7 (scaled from 0 to 10)***
2. ***GHG Emissions Reduction: 8***
3. ***Energy Consumption: 6***
4. ***Lifecycle Analysis (GWP): 7***
5. ***Waste Management Efficiency: 9***
6. ***Water Consumption: 5***
7. ***Type of Plastic Recycled: 8***
8. ***Resource Conservation: 7***
9. ***Biodiversity Impact: 6***
10. ***Pollution Control: 9***

Step 3: Weighted Scores

Weighted Score=Score × Weight

1. ***Volume of Plastic Recycled:*** *7×0.1=**0.7***
2. ***GHG Emissions Reduction:*** *8×0.1=**0.8***
3. ***Energy Consumption:*** *6×0.1=**0.6***
4. ***Lifecycle Analysis (GWP):*** *7×0.1=**0.7***
5. ***Waste Management Efficiency:*** *9×0.1=**0.9***
6. ***Water Consumption:*** *5×0.1=**0.5***
7. ***Type of Plastic Recycled:*** *8×0.1=**0.8***
8. ***Resource Conservation:*** *7×0.1=**0.7***
9. ***Biodiversity Impact:*** *6×0.1=**0.6***
10. ***Pollution Control:*** *9×0.1=**0.9***

Step 4: Index Score

Overall Index:

7.2

F. Plastic-to-Oil: Impact on Economy, Environment and Society - Research Results Part Three

F. Economic Effects

enespa® green technologies

1. **Market Value of Recycled Oil:**
   - **Revenue Generation**: The sale of oil produced from plastic recycling can generate significant revenue. For instance, with an estimated conversion efficiency of 70% and global plastic waste of 300 million metric tons/year, if 20% is recycled, the potential revenue at $500/ton (assuming an average oil price of $67/bbl.) would be **$21 billion annually**.

2. **Job Creation:**
   - **Employment Opportunities**: The establishment and operation of plastic-to-oil plants create jobs in manufacturing, engineering, and operations. Each facility can employ hundreds of workers directly and indirectly.

3. **Investment and Innovation:**
   - **Capital Investment**: Initial investment in technology and infrastructure can stimulate economic activity. According to industry reports, the global market for waste-to-oil technologies could attract billions in investment.
   - **Research and Development**: Continuous innovation in this field can lead to advancements in related technologies, fostering a cycle of innovation and economic growth.

4. **Cost Savings:**
   - **Waste Management**: Reducing the volume of plastic waste can lower municipal waste management costs. For example, diverting 20% of plastic waste from landfills can save millions in disposal fees annually.

F. Environmental Effects

enespa® green technologies

1. **Reduction in Plastic Waste:**
   - **Waste Diversion:** Converting plastic to oil reduces the amount of plastic ending up in landfills and oceans. For example, recycling 20% of global plastic waste (60 million tons) can significantly decrease environmental pollution.

2. **Reduction in Greenhouse Gas Emissions:**
   - **Lower Emissions:** Converting plastic to oil emits fewer greenhouse gases compared to traditional plastic incineration or landfill decomposition. The process itself can be optimized to minimize emissions.
   - **Life Cycle Emissions:** Using recycled oil instead of crude oil can reduce emissions associated with extraction, refining, and transportation of crude oil.

3. **Resource Conservation:**
   - **Circular Economy:** Plastic-to-oil technology promotes a circular economy by transforming waste into valuable resources, reducing the need for virgin plastic production and conserving natural resources.

F. Social Effects

1. **Public Health Benefits:**
   - **Reduced Pollution:** Less plastic waste in the environment reduces pollution-related health issues, such as respiratory problems caused by burning plastic or water contamination from plastic debris.
   - **Cleaner Communities:** Effective waste management leads to cleaner living environments, improving overall quality of life.

2. **Awareness and Education:**
   - **Environmental Awareness:** Implementing such technologies raises public awareness about waste management and sustainability, encouraging more responsible consumption and waste disposal behaviors.

3. **Investment and Innovation:**
   - **Local Economic Boost:** Establishing recycling facilities can stimulate local economies, providing jobs and business opportunities, especially in regions struggling with waste management issues.