Environment International 172 (2023) 107693

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

A high-resolution dynamic probabilistic material flow analysis of seven plastic polymers; A case study of Norway

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ARTICLE INFO

Handling Editor: Thanh Nguyen

Keywords:
Material flow analysis
Dynamic probabilistic MFA
Plastics
Industrial sectors
Polymer

ABSTRACT

Plastic pollution has long been identified as one of the biggest challenges of the 21st century. To tackle this problem, governments are setting stringent recycling targets to keep plastics in a closed loop. Yet, knowledge of the stocks and flows of plastic has not been well integrated into policies. This study presents a dynamic probabilistic economy-wide material flow analysis (MFA) of seven plastic polymers (HDPE, LDPE, PP, PS, PVC, EPS, and PET) in Norway from 2000 to 2050. A total of 40 individual product categories aggregated into nine industrial sectors were examined. An estimated 620 ± 23 kt or 114 kg/capita of these seven plastic polymers was put on the Norwegian market in 2020. Packaging products contributed to the largest share of plastic put on the market (~40%). The accumulated in-use stock in 2020 was about 3400 ± 56 kt with ~60% remaining in buildings and construction sector. In 2020, about 460 ± 22 kt of plastic waste was generated in Norway, with half originating from packaging. Although ~50% of all plastic waste is collected separately from the waste stream, only around 25% is sorted for recycling. Overall, ~50% of plastic waste is incinerated, ~15% exported, and ~10% landfilled. Under a business-as-usual scenario, the plastic put on the market, in-use stock, and waste generation will increase by 65%, 140%, and 90%, respectively by 2050. The outcomes of this work can be used as a guideline for other countries to establish the stocks and flows of plastic polymers from various industrial sectors which is needed for the implementation of necessary regulatory actions and circular strategies. The systematic classification of products suitable for recycling or be made of recyclate will facilitate the safe and sustainable recycling of plastic waste into new products, cap production, lower consumption, and prevent waste generation.

1. Introduction

Plastic pollution is characterized as a planetary boundary threat due to global exposure and irreversible impacts on the earth's system (Arp et al., 2021; Macleod et al., 2021; Villarrubia-Gómez et al., 2018). The immense quantity and diversity of plastic waste already exceeds the threshold of the planetary boundary under which humanity can survive in the future (Persson et al., 2022). Triggered by the global outcry over the environmental impacts of plastic pollution, many governments began implementing bans and regulations on the use of single-use plastics over the past decade. Yet, many of these efforts lack implementation strategies to effectively reduce plastic pollution (Xanthos and Walker, 2017). Even by implementing the best available political and technological solutions, such as improved waste management and increased recycling and reuse rates, the global emission of plastic to the environment is estimated to reach up to 53 million tonnes (Mt) per year by 2030 (Borrelle et al., 2020). Yet, under the most ambitious mitigation scenarios, annual plastic emissions cannot be reduced by more than 78%, which translates into the accumulation of 710 Mt of plastic waste in the environment by 2040 (Lau et al., 2020).

In 2022 the 5th United Nations Environment Assembly (UNEA 5.2) called for immediate action to develop an international binding agreement to include measurable targets and action plans, adopting strong plastic pollution reduction measures, and strengthening regional and global cooperation and evidence-based decision-making across the full plastics lifecycle (UNEP, 2022). The European Commission (EC), under the European Green deal and related initiatives, requires member states to take adequate measures toward the Zero Pollution Action plan, which requires a 50% reduction of plastic litter in the sea, a 30% reduction in the release of microplastic into the environment, and a 50% reduction in generation of municipal waste by 2030 (European Commission, 2021). Furthermore, through the EU plastic strategy and several directives

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https://doi.org/10.1016/j.envint.2022.107693
Received 28 October 2022; Received in revised form 10 December 2022; Accepted 11 December 2022
Available online 12 December 2022
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(e.g., single-use plastic (2019/904), plastic bags (2015/720), waste trade (2020/2074, 1418/2007)), the EC aims to protect the environment and human health by reducing marine litter, greenhouse gas emissions, and dependence on imported fossil fuels. The realization of all these objectives would be immediately reliant on reduced production and consumption of plastics. As such, the EC set a target of recycling 50% of plastic packaging by 2025 and 55% by 2030 (EC, 2018).

In August 2021, the Norwegian government released its new ambitious plastic strategy considered a critical step toward a circular economy for plastic. The government's vision is to have a more renewable value chain for national, regional, and global plastic, which requires an increase in plastic recycling and maximizing the reuse of plastic for as long as possible (Klima- og miljødepartementet, 2021). The Norwegian targets are set in accordance with the EC's and require the recycling of 50% of plastic packaging by 2025 and 55% by 2030 (The Norwegian Ministries, 2022). However, in 2020, it was reported that of the 540 kt of all plastic waste generated annually in Norway only about 24% is successfully collected for recycling and only 9% of recyclate (recycled plastic) is used by Norwegian industries (Handelens Miljøfond, 2020). Further estimates also depicted that of the 220 kt plastic packaging put on the market in 2017 in Norway, 150 kt (~70%) was not recycled (Deloitte, 2019). This implies that to achieve the targets set by the EC and the Norwegian government, Norway must increase its recycling capacity for plastic waste by at least 70% by 2025 and 120% by 2030 (Deloitte, 2019). Despite the existence of effective waste management infrastructure and advanced technologies, Norway does not have the full capacity to manage all plastic waste generated domestically. An adequate understanding of major industrial activities at the private and industrial levels due to the lack of harmonized and reliable data on the amounts and characteristics of plastic waste generation prevents the authorities from taking effective actions to reduce plastic waste pollution. Failure to identify potential opportunities impedes achieving planned targets, and subsequently leads to the downward adjustment or postponement of ambitious future targets. This urges a fundamental transformation of the plastic economy to valorize end-of-life plastic products at the sectoral level and a systematic identification of product categories which can be reused and/or recycled to impede the growth of plastic production and consumption.

Identifying barriers and potentials for both reducing waste generation and improving waste management is critical for a successful transformation. As such, a comprehensive understanding of the flow of plastic products through their life cycle from global production and use to waste streams at a regional scale is critical for devising mitigation strategies and effective planning for waste reduction. Material Flow Analysis (MFA) is a scientific modeling approach for quantifying the flows of elements, compounds, and materials through the anthroposphere (Brunner and Rechberger, 2004). MFA has been used extensively in recent years in waste management (Allesch and Brunner, 2017) to analyze the flow of plastics through societies (Bogucka et al., 2008; Cullen et al., 2020; Joosten et al., 2000; Mutha et al., 2006; Patel et al., 1998; Van Eygen et al., 2016). A very detailed study on the flow of different plastic polymers by Kawecki et al. (2018) provides detailed stocks and flows of seven commodity plastics (polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), expanded polystyrene (EPS), polystyrene (PS), and polyethylene terephthalate (PET)) in Europe and Switzerland from production to waste treatment in 2014. They further extended this work by building a dynamic probabilistic MFA (DPMFA) model for the same seven polymers from 1950 to 2016 for Europe (Kawecki et al., 2021). By establishing a full life-cycle model capturing essential details of product sectors over time, they identified potentials for future policy interventions to account for the current in-use stock of plastics entering the waste stream in the coming years. A dynamic model for three (PE, PET, and PP) plastic polymers in Europe was also developed by Eriksen et al. (2020). The authors evaluated the circularity of these polymers in a baseline scenario as well as five different scenarios over the next 50 years. They concluded that focusing on the recycling rate of plastic alone was insufficient for the transition toward circularity and a reduction in the demand for plastics must also be considered. The outcomes of these studies provide a system-based assessment of plastic polymer flows illustrating the magnitude of the plastic waste problem in Europe and its criticality to devise effective waste management strategies. However, the challenge remains to be addressed at the national and regional scales where consideration should be given to differences in waste management technologies, industrial sectors and activities, solid waste characteristics, and social and demographic parameters. This is a particular challenge for Norway as one of the most waste-generating countries per capita in Europe with heterogeneous waste management systems across the country (Eurostat, 2022). Thus, effective national strategic planning should be devised based on a high spatial resolution assessment of end-of-life treatment of plastic waste. The prerequisite for successful planning at the national level is to (a) identify major industrial sectors, (b) characterize the plastic polymer type for each industrial sector, (c) anticipate the evolution of each polymer waste generation according to supply and demand in each industrial sector, and (d) identify the potential opportunities for each industrial sector to reduce and/or reuse or recycle plastic waste.

This study aims at filling this knowledge gap by establishing the plastic inventory of Norway using a dynamic probabilistic MFA model. The plastic inventory refers to stocks, flows, and sinks of seven polymer types used in nine industrial sectors including various stages of production, manufacturing, consumption, and waste management from 2000 to 2050. These seven polymers make up around 73% of plastics demand in Europe (Plastics Europe, 2020) and are easily identified by consumers in most countries through the resin identification code (from one to six marked in an equilateral triangle) (American Chemistry Council, 2021; United Nations Environment Programme and Consumers International, 2020).

In the following section, we describe the method employed including the conceptual model setup, data collection, and model implementation. Subsequently, results are presented for each industrial sector by polymer type. We compare our results to previously published MFA studies for different European countries and to official plastic statistics from Norway. Finally, we identify potential areas for improvement at the sectoral level for plastic recycling and the use of recyclate within or across industrial sectors, highlight obstacles that hinder plastic recycling, and provide recommendations for policy interventions based on the study outcomes.

2. Methods

In this study, we modeled Norwegian plastic flows, stocks, and sinks using a dynamic probability material flow analysis. The flows in Norway were modeled as a single entity without regional variation. The term flows refer to the amount of a good or substance flowing in or out of a process per time, stocks are goods or substances that are stored in a process for a certain amount of time, and sinks refer to the final environmental or end-of-life treatment of a good or substance at the end of their use-phase. Seven polymers are included in the study: LDPE, HDPE, PP, PS, EPS, PVC, and PET. The basis for the model is the DPMFA developed by Kawecki et al. (2021), hereafter referred to as the base model. The base model applies the DPMFA Python package developed by Bornhöft et al. (2016) and uses the model setup from the static probabilistic material flow analysis for seven plastic polymers in Europe by Kawecki et al. (2018). Details on the method and the model setup can be found in the referred articles.

In general, an MFA first defines the system in question, the inflows into the system, and the transfer coefficients (TCs). The inflows can be separated into the import of finished or semi-finished products from outside the system boundary or the production of virgin or recycled material inside the system boundary. The TCs describe the partitioning of the mass in one process into the next. The mass in every compartment is multiplied by the corresponding TCs to obtain the mass in the following compartments (Brunner and Rechberger, 2004). A dynamic MFA also incorporates the time (i.e., years) a product is used before being discarded and entering the waste stream by assigning a lifetime to each individual product category. This results in stocks of products being used for several years before ending up in the waste stream. The probabilistic component of the models allows us to include the uncertainty of all flows by expressing probability distributions for all inflows, TCs, and lifetimes. For the inflows and TCs, a pedigree matrix approach developed by Laner et al. (2015) was used to define key parameters for the uncertainty distributions that allow for the conversion of qualitative data quality indicators into quantitative measures. The same method has already been used by Kawecki et al. (2018) and Van Eygen et al. (2017) to calculate uncertainty coefficients associated with parameters in their models. The pedigree matrix with the five different data quality indicators and the corresponding data quality levels can be found in the supporting information in Table S1. For more details on exactly how to calculate the probability distributions, the reader is referred to Laner et al. (2015). Next, the model is run 10,000 times sampling a value from the chosen Bayesian distribution for each inflow, TC, and lifetime and calculating a result for each iteration of the Monte Carlo simulation. Considering all iterations, the mean and standard deviations for each flow, stock, or sink can be calculated.

2.1. Model setup

The model consists of six processes at the production and manufacturing stage, nine industrial sectors with 40 individual product categories, 13 processes of the waste collection system, six processes of the recycling system, and eight final sinks. Five of the final sinks are anthropological sinks such as landfill, incineration, export, or reuse and recycling, while two sinks are environmental compartments such as ocean and wastewater treatment plant (WWTP). However, releases into the environment were not explicitly modeled and were only considered for release to water of down-the-drain products such as shampoos that contain primary microplastics and fishing gear that is lost at sea. No conclusions on the total emission of plastic to water or other environmental compartments should be drawn based on these estimates. The whole structure of the material flow model with all processes and how they are connected is shown in Figure S1. Table 1 summarizes all processes and industrial sectors at different stages of their life cycles that were considered in this study.

2.2. Data collection

The study has a temporal scope from 2000 up to 2050. This time frame was chosen because reliable trade data and waste statistics are available from the early 2000s onward, and the current stock of plastic products was assumed to be made-up of products that entered the market after 2000. A time-series was defined for all parameters (inflows, trade, and TCs) for each of the seven polymers for each year.

Transboundary trade of plastic polymers from 2000 to 2020 was calculated using harmonized system (HS) data (The Norwegian Ministries, 2022) from Statistics Norway (Statistisk sentralbyrå (SSB)) and the polymer composition of products from Kawecki et al. (2018) and InforMEA (2022). For the years 2021 to 2050, we assumed a business-as-usual (BAU) scenario meaning that inflows were scaled from the 2020-value based on GDP projections (OECD, 2018) according to Eq. (1):

$$F_{i,t} = F_{i,2020}/GDP_{2020} * GDP_t \qquad (1)$$

Where $F_{i,t}$ is the trade flow (F) of a certain polymer i in year t, $F_{i,2020}$ is the trade flow for the same polymer i in 2020, GDP_t is the forecasted GDP in Norway in year t, and GDP_{2020} is the GDP in Norway in 2020 (OECD, 2018).

Recycled material production data and primary production data for 2018 were taken from the report by Handelens Miljøfond (2021). Previous and future years were extrapolated using GDP data (OECD, 2018) according to Equation (1), by substituting $F_{i,2020}$ and GDP_{2020} with $F_{i,2018}$ and GDP_{2018}, respectively. For a detailed description of the calculation of the inflows, see section S2 (Recycled material production), section S3 (Primary production), and section S4 (Trade) in the supporting information. All inflows including their data source and quality indicators can be found in the database (DPMFA_Plastic_Norway.db) in the table “Input”.

The TCs for the years 2000 to 2020 were calculated using databases, reports, and published studies, which are summarized in the supporting information (section S5). Whenever possible, TCs were calculated and adapted for Norwegian sectors. When no Norwegian data was available, the European TCs from the base model were adopted. For example,

Table 1
Processes and industrial sectors considered in the MFA based on their life cycle stage. *Household textiles and technical textiles are summarized in the results as “Other textiles”. $^{+}$Material reuse, part reuse, and textile reuse are summarized in the results as “Recycling and reuse”. $^{\#}$Ocean and WWTP are summarized in the results as “Water”. ASR: auto shredder residue; EEE: electrical and electronic equipment; ELB: End-of-life boats; ELV: End-of-life vehicles; HH: Household; WEEE: Waste from electrical and electronic equipment; WEEP: Waste of electrical and electronic plastic; WWTP: Wastewater treatment plant. Pant bottles refer to deposit return system.

Production and manufacturing	Industrial sectors and individual product categories			Waste collection	Recycling system	Sinks
- Recycled material production - Primary production - Inventory - Fiber production - Non-textile manufacturing - Textile manufacturing	- Packaging: *HH bottles,* *HH bags,* *HH foil,* *HH rigid plastic* *HH EPS,* *HH mix,* *Industry bags,* *Industry foil,* *Industry rigid plastic,* *Industry EPS,* *Industry mix,* *Agriculture foil,* *Agriculture mix* - Construction: *Pipes,* *Insulation,* *Coverings,* *Profiles,* *Lining*	- Agriculture: *Agricultural film,* *Agricultural pipes,* *Agricultural other* - Automotive: *Automotive* - EEE: *EEE* - Boats *Boats* - Other plastic: *Household plastic,* *Furniture,* *Cosmetics,* *Other plastic products,* *Fabric coatings*	- Clothing: *Clothing* - Household textiles*: *Household textiles* - Technical textiles*: *Building textiles,* *Geotextiles,* *Agrotextiles,* *Mobility textiles,* *Fishing gear,* *Hygiene and medical textiles,* *Technical clothing,* *Technical household textiles,* *Other technical textiles*	- Pant bottles - Mixed waste - Packaging waste - Construction & demolition recyclables - Construction & demolition incinerables - Agriculture waste - ELV - ELV textiles - ELB - Fishing gear waste - WEEE - Textile waste - Pre-consumer waste	- Packaging recycling - Construction & demolition recycling - Agriculture recycling - Large automotive parts - ASR - WEEP	- Incineration: *Elimination* - Landfill Material reuse^{+} - Part reuse^{+} - Ocean$^{\#}$ - WWTP$^{\#}$ - Textile reuse^{+} - Export

Norwegian TCs were specifically calculated for packaging (Private communication with Grønt Punkt Norge, June 2021), PET bottle collection (Infinitum, 2020; Norsk Resirk, 2012), boats (Statens forurensningstilsyn, 2008), fishing gear (Deshpande et al., 2020), and clothing and household textiles (Watson et al., 2020). Between 2000 and 2020, where time-series data for a specific year were not available in databases or literature, the data points were either interpolated linearly between two existing estimates or set equal to the nearest data point. For 2021 and onward, TCs were kept constant (i.e., the same value as for 2020). All TCs, as well as their associated quality indicators and source, can be found in the database in the table “Transfercoefficients”. The lifetimes were taken from Kawecki et al. (2021), except for boats that were taken from Mepex (2014), and fishing gear from Deshpande et al. (2020). For a complete list of all the lifetime distributions, see the database table “Lifetimes” or section S6 in the supporting information.

All input data and parameters, as well as the model algorithm, are subject to a degree of uncertainties and variability. The Bayesian distribution incorporated into the model allows for accounting of uncertainty and variability by assigning a confidence interval based on data quality indicator scores (dqis). All input parameters, such as inflows and TCs, and their associated dqis can be found in the supporting database (DPMFA_Plastic_Norway.db).

2.3. Model implementation

Building on Kawecki et al. (2021), the model was implemented as a python research code in addition to a SQL database. Data input was done via excel files, which were subsequently uploaded to the SQL database. The database contains all the input data needed to run the model, while the python code uses the data in the database as input and executes the calculations. The latest version of the research code used for this paper is made available under CC BY-NC-SA 4.0 license at https://git.nilu.no/IMPACT/plastcycle. Note that the model is under continuous development and that the version available may have been further developed after the publication of this article. The specific version used for this article is archived on Zenodo (https://zenodo.org/record/7220273).

3. Results

In the following sections, the modeling results are presented by industrial sector and split into the different polymers. Aggregated results per polymer are available in the supporting information in section S7.

3.1. MFA of all seven polymers

The flows of seven plastic polymers from the put-on-the-market (POM) stage to stocks and waste management in 2020 is demonstrated in Fig. 1. Several flows and compartments are aggregated for better readability. For example, the individual product categories are aggregated into their industrial sectors, and the waste treatment processes for all sectors are aggregated into mixed waste collection and separate waste collection. Further, (a) household textiles and technical textiles are aggregated into other textiles, (b) material reuse, part reuse, and textile reuse into recycling and reuse, and (c) WWTP and ocean into water in the MFA flow diagram and the following result figures. It should be noted that the black bars illustrate the total flow of each process, not the stocks. The stocks, waste production, and accumulation in different sinks throughout the years are discussed in more detail below. The interactive version of this figure with specific flows for each polymer type is available on the journal’s website.

An estimated total of 620 ± 23 kilotonnes (kt) or 114 kg/capita (population data from SSB (2022a)) of plastic was put on the market in 2020. The total amount of POM includes the domestic production of virgin raw material or recycled material (~10%) and imported plastics within semi- and finished products (~90%). Of the total 3400 ± 56 kt (630 kg/capita) of plastic in in-use stocks, the majority is found in construction (~60%), followed by EEE (~15%) and other plastic (~10%). The total of 460 ± 22 kt of plastic waste is generated (83 kg/capita) from the nine industrial sectors of which 51% was incinerated, 23% was recycled or reused, 16% was exported, and 10% entered landfills.

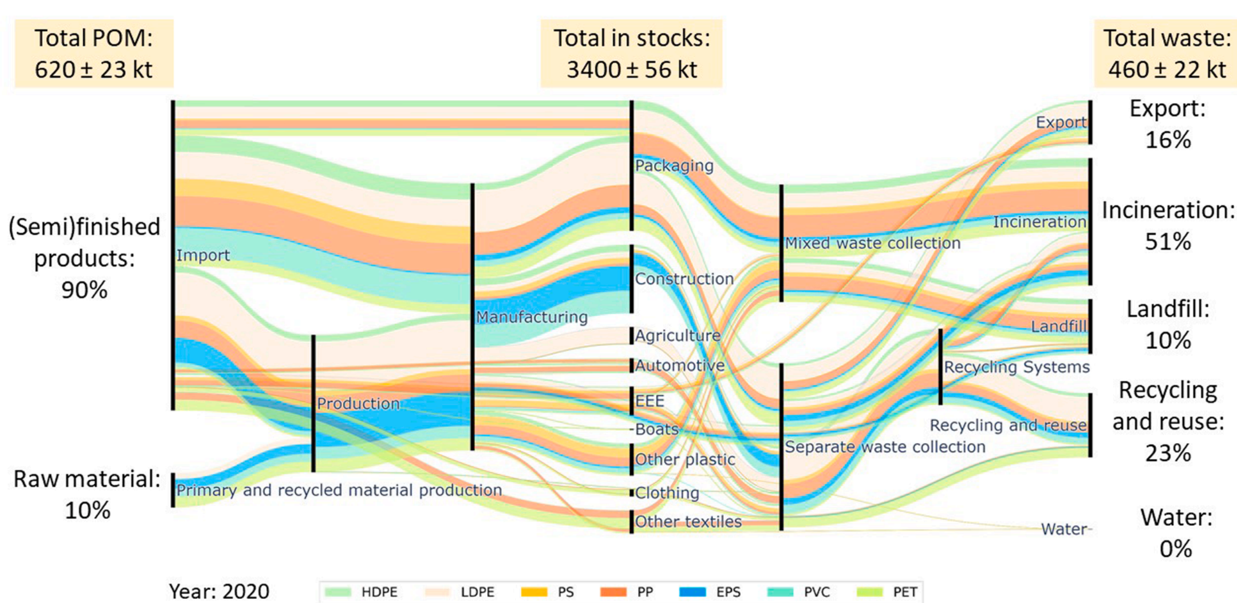

Fig. 1. Plastic flows, stocks, and waste generation in Norway in 2020 from production to waste. The flows are color coded by polymer (HDPE, LDPE, PS, PP, EPS, PVC and PET) and the sums of all seven polymers are shown for plastic put on the market, total stocks, and total waste generation. For an interactive figure with the flows and stocks shown for each polymer, see the supporting information on the journal’s website. EEE: electrical and electronic equipment.

3.2. Plastic put on the market (POM)

The temporal trend of all plastic polymers POM in Norway depicts that the current amount of plastic put on the market increased by 110% from 2000 and it is expected to further increase by 65% under the BAU scenario by 2050. The breakdown of polymer type for each industrial sector entering the Norwegian market from 2000 to 2050 is presented in Fig. 2, where the solid line and the shaded area represent the mean value and the standard deviation of a given data point, respectively. The standard deviation increases over time due to increasing uncertainties associated with assumptions and parameters for future projections. Packaging products made up the largest share of POM plastic, which is ~40% of the total amount in 2020. Construction and other plastics follow behind with ~25% and ~10%, respectively. Plastic packaging is made up of all seven polymers, dominated by LDPE (~40%), PP (~20%), and PET (~17%), while other industrial sectors consist of one or two major polymer types. For instance, agricultural plastic is mainly made up of LDPE (~95%), automotives are made of mainly PP (~60%), boats and clothing are almost exclusively made of PET, and other textiles are dominated by PET (~50%) and PP (~45%).

3.3. In-use stocks of plastics

In 2020, the total in-use stock of plastics in Norway was estimated to be around 3400 ± 56 kt. The construction sector consists of ~60% of the total stock followed by EEE (~15%) and other plastic (~10%). The distribution of the polymers in stocks mainly follows the pattern of which polymers are put on the market in each industrial sector presented before. The mass of plastic in stock is expected to increase by 140% by 2050 under BAU. The stocks in the early 2000s are most likely underestimated since the model started only in 2000 and products put on the market prior to 2000 are not considered.

The stacked stocks of various polymers in the nine industrial sectors over time are presented in Fig. 3. The in-use stocks of plastic are dependent upon the amounts of POM plastics within products and the products' lifetime. For example, plastic packaging is often designed for a single use and therefore leaves the market the same year it is produced (CIEL, 2019). Thus, the stock of plastic used in packaging is relatively small despite the large quantity of plastics entering the market every year. The plastic used for construction on the other hand has a long lifetime, in some cases up to 80 years (APME, 1995), which then keeps the in-use stock of plastics significantly larger than other sectors. In 2020, EPS (820 ± 26 kt) and PVC (640 ± 25 kt) used in construction sectors are the main polymers in in-use stocks, followed by HDPE (270

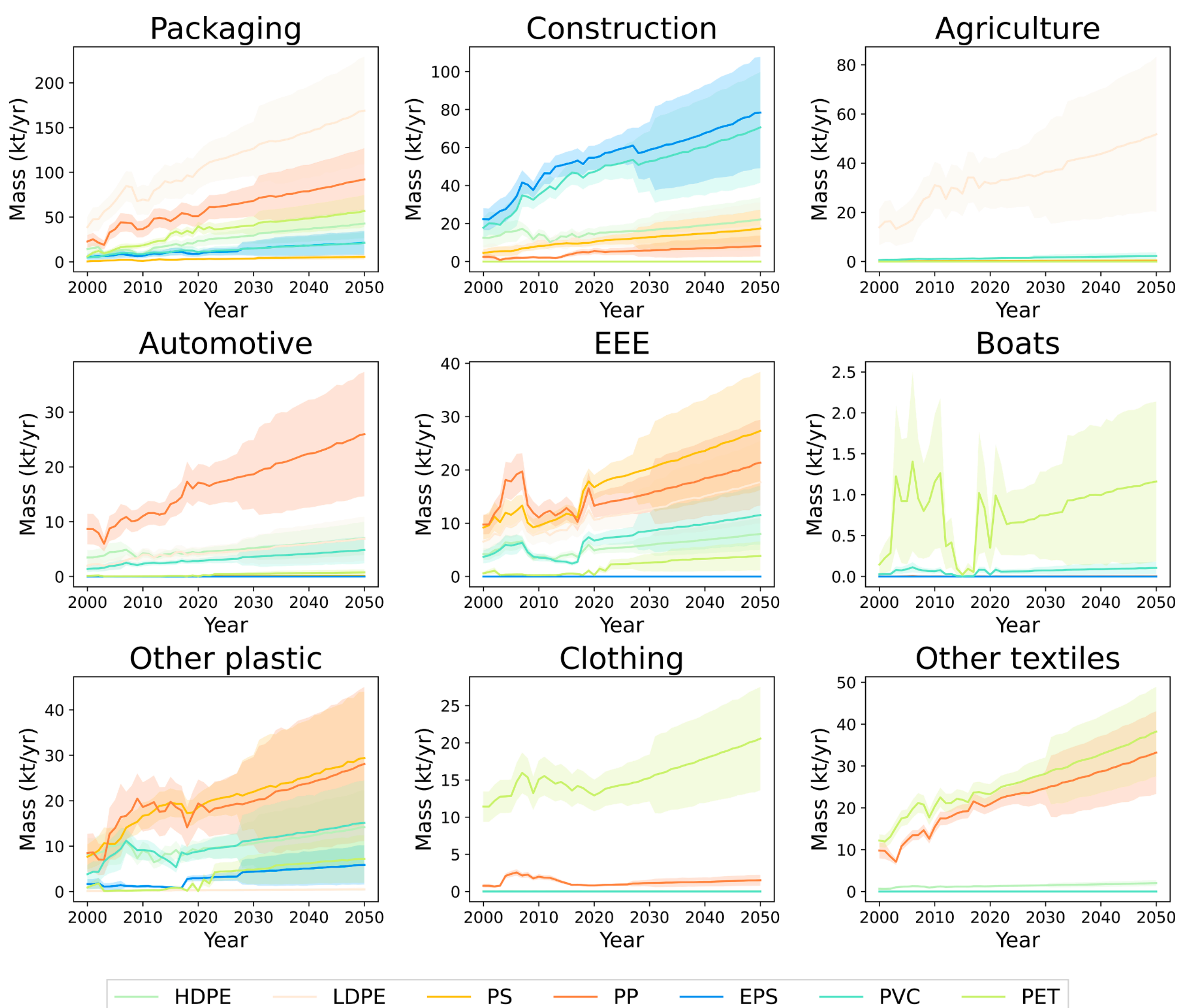

Fig. 2. Amounts of plastic polymers (in kt/year) put on the market in Norway from 2000 to 2050 by industrial sector. Graphs show the mean as a solid line and the standard deviation as shaded area. EEE: electrical and electronic equipment.

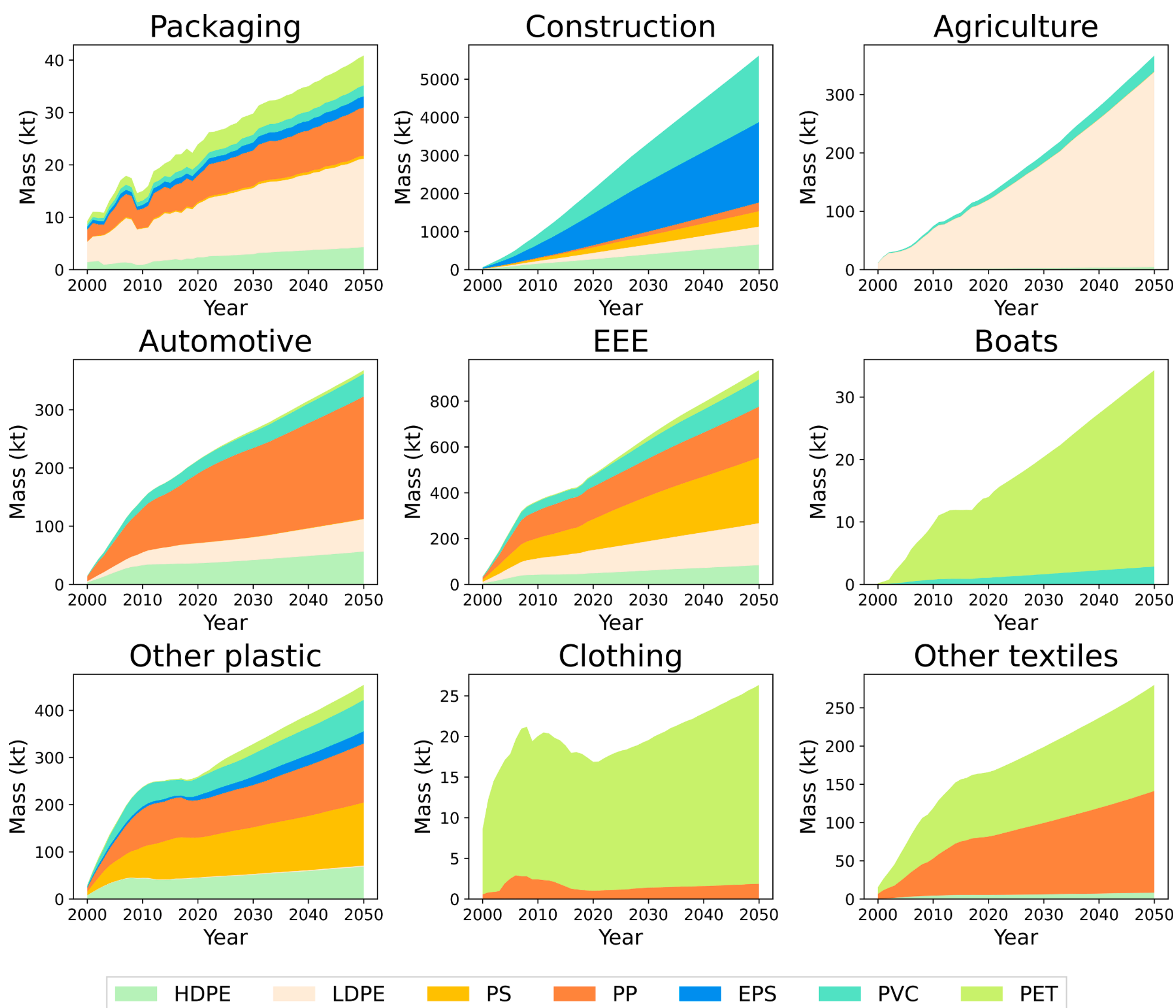

Fig. 3. Mass of plastic (in kt) in use for the nine different industrial sectors color coded by polymer in Norway from 2000 to 2050. Graphs show the means of the probability distributions. EEE: electrical and electronic equipment.

± 16 kt), LDPE (170 ± 14 kt) and PS (150 ± 8.1 kt) likewise in construction, PP (140 ± 6.3 kt) and PS (130 ± 5.3 kt) in EEE, LDPE in agriculture (120 ± 13 kt), and PP in automotives (120 ± 7.2 kt).

3.4. Waste generation

A total of 460 ± 22 kt of plastic waste was estimated to enter the waste stream in 2020 from the nine industrial sectors in Norway, which depicts a significant increase of 350% since 2000 when the annual plastic waste generation was about 100 kt (Figure S4). If no further mitigation measures are taken, under the BAU scenario, the amount of plastic waste generation will increase by nearly 90% by 2050. Plastic packaging comprises ~50% of the total waste generated in 2020, followed by other plastics (~12%) and other textiles (~10%). Fig. 4 shows the plastic waste generation per industrial sector for each of the seven different polymers from 2000 to 2050. The overall flow of LDPE comprises ~30% of the total waste generation, mainly from packaging (~25% of total waste generation or ~70% of LDPE waste generation) and agriculture (~6% or ~20%), followed by PP (~25%), mainly from packaging, other textiles, or other plastic. PET (~17%) has the third largest flow from mainly packaging, other textiles, and clothing. The sharp increase in PET flow to waste from the boat and clothing industrial sectors between 2020 and 2030 reflect the large in-use stock of these products prior to 2020. The flows of EPS, PS, and PVC from construction; LDPE from agriculture; PS, PP, and LDPE from EEE; and PP, PS, HDPE, and LDPE from the other plastic sector are also expected to steadily increase following 2020 as the large quantity of products in the in-use stock reaches the end-of-life stage over time.

Plastic waste is either collected with municipal solid waste to be mainly incinerated or collected separately for recycling within and/or outside of Norway. Of the total plastic waste generated in Norway, about 50% (230 ± 12 kt) was collected separately in 2020 and the rest was treated with mixed waste (see section S5 in the supporting information). Half of the separately collected plastic waste is coming from products from the packaging sector, dominated by LDPE and PET. The highest separate collection rate in packaging is found for PET with ~70% followed by LDPE (~60%) and EPS (~45%). Considerable amounts of plastic are also collected separately from agriculture, automotive, construction, and EEE, each contributing to ~10% of the total separately collected waste. The amounts of the various plastic polymers separately collected over time for each industrial sector are presented in Fig. 5.

The temporal trend in the treatment of plastic waste for each industrial sector is presented in Figure S5. Overall, the rate for separately collected waste for packaging, EEE, clothing, and other textiles is about 50% of the total waste generated. Nearly 100% of all plastic waste from the industrial sectors construction, agriculture, automotive, and boats

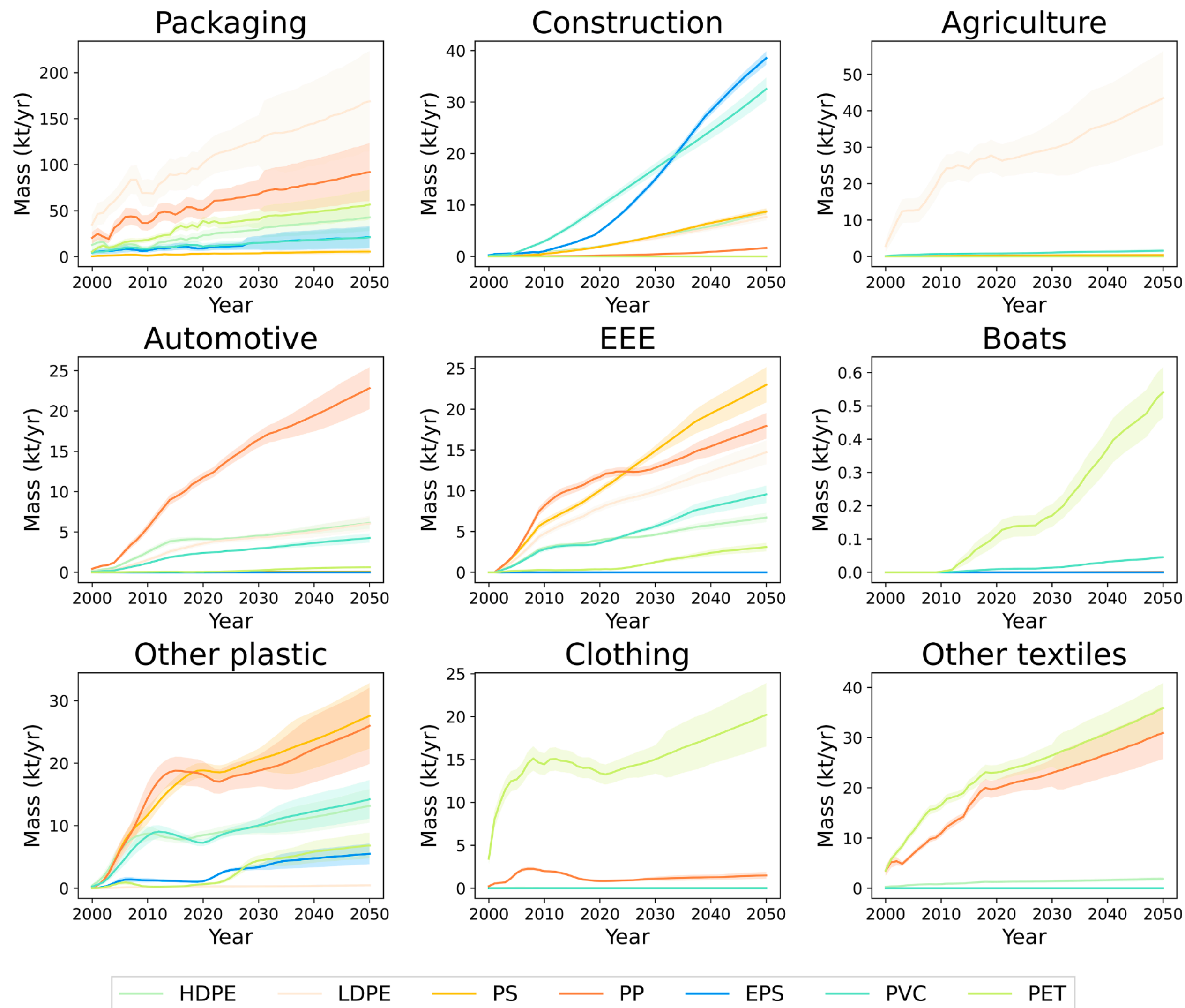

Fig. 4. Waste generation (in kt/year) of seven plastic polymers from different industrial sectors in Norway between 2000 and 2050. Graphs show the mean as a solid line and the standard deviation as shaded area. EEE: electrical and electronic equipment.

are collected separately, while only ~1% of plastic waste from the 'other plastic' sector is collected separately with the rest entering the mixed waste stream.

It should be emphasized that separately collected waste does not necessarily refer to the recycling or reuse of plastics in Norway. Some of the separately collected plastic that cannot be recycled due to difficulties in the separation of different plastic polymers, contamination, or lack of capacity in proper recycling of plastic waste at the regional scale, will end up mainly in incinerators.

3.5. Sinks of plastics and recovery rate of plastics

A total of eight sinks were considered in this study but shown as aggregated five final sinks of incineration, recycling and reuse, landfill, export, and water in related figures. Since the releases into the environment were not explicitly modeled and only the release of microplastic in cosmetics to the wastewater and loss of fishing gear in the ocean are considered in this study, no conclusions on total emissions of plastic to the environment should be drawn based on these estimates. Under the BAU scenario, the quantity of plastics in sinks will quadruple by 2050 from its current level. Fig. 6 illustrates the evolution in each individual sink with the contribution of each polymer type over time. The sink 'water' comprises mainly PET, PP, and HDPE, while incineration, landfill, export, and reuse and recycling are dominated by LDPE, PP, and PET. The evolution of the total mass in the final sinks of all plastic polymers, where they have been accumulated after waste collection or treatment processes over time, is presented in Figure S6.

3.6. Comparison of plastic POM, stocks, and waste in Norway

Table S3 summarizes the absolute values of the quantity of plastic polymers entering the market (POM), remaining in in-use stocks, entering the waste stream, and accumulating in final sinks in Norway in 2020. The flow of POM plastics is dominated by LDPE and PP, followed by PVC and PET, while the in-use stock is dominated by EPS and PVC. In the waste stream, LDPE, PP, and PET are the major contributors to the total annual plastic waste generation. Based on our estimates, LDPE, EPS, PET, and PVC have the highest separate collection rate in comparison with other polymer types. The probabilistic approach of this study allowed for the incorporation of parameter uncertainties and variabilities into the model, which are reported as ± standard deviation in Table S3.

The magnitudes of the plastic POM, plastic in stocks, and the generated waste for each of the nine industrial sectors in 2020 by the various polymers are presented in Figure S7. Even though most plastic is put on the market for packaging, more than ten times that amount can

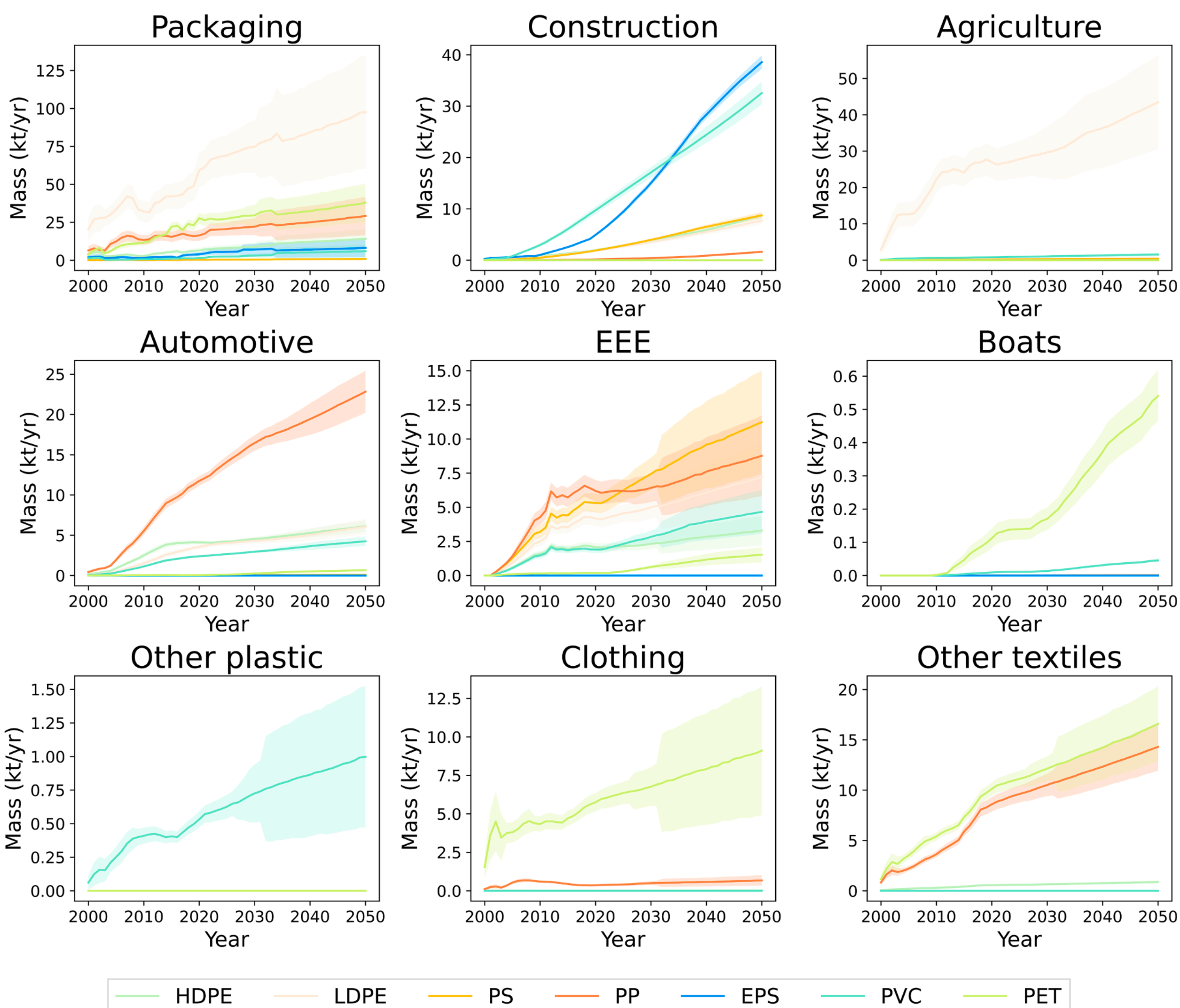

Fig. 5. Amounts of plastic polymers (in kt/year) separately collected in Norway from 2000 to 2050 by industrial sector. Graphs show the mean as a solid line and the standard deviation as shaded area. EEE: electrical and electronic equipment.

be found in building and construction stocks. The stocks of plastic packaging on the other hand are barely visible in the figure due to their very fast turnover and short product lifetime. Plastics used in construction, automotive, or EEE have a long lifetime and are used for decades before being discarded. In general, the amount of plastic in stocks is increasing when more plastic is put on the market than is discarded. Thus, a significant increase in in-use stocks is expected for these industrial sectors as is shown in Fig. 3. The relative uncertainty of the inflows into each compartment for all seven polymers in 2020 is presented in Figure S8.

4. Discussion

4.1. Uncertainty associated with the model parameters and results

This study presents the first comprehensive high-resolution overview of seven plastic polymer flows in Norway from production and manufacturing, through the use phase in different industrial sectors, to waste treatment and final sinks. The model uses data from several sources for the flows from 2000 to 2020 and a business-as-usual approach to extrapolate the flows up to 2050. This study included industrial sectors with rapid turnovers such as packaging, as well as industrial sectors with long lifetimes such as construction, automotives, or electronics.

To evaluate the model outcomes, the results were compared with waste generation and collection data for Norway that were collected and compiled by SSB (Table 2). The quantity of plastic waste generation for 2020 estimated in this study for the packaging and the agriculture sector are 9% and 17%, respectively, higher than those reported by SSB. The difference could be due to data gaps, unharmonized data, lack of precision in waste data reporting and/or inconsistence reporting procedure by various stakeholders to SSB. In addition, the quantity of POM, in-use stock, and plastic waste generation in Norway was approximated for several industrial sectors for 2018 (supporting information section S8 and Table S4) using openly available publications and documents as well as inputs from industries (Handelens Miljøfond, 2020). The lower in-use stock of plastic packaging estimated by Handelens Miljøfond (2020) in comparison with our results can be attributed to the differences in the definition of the in-use stock for products with short lifespans. It appears that our model underestimated the amount of plastic used in boats and fishing gear, most likely due to the limited number of product categories included here and a lack of reliable data on the fraction of plastic used in these sectors. Given the importance of boats and fishing gear in Norway, more detailed data could provide more reliable results on the quantity of waste generation, collection, and loss in these sectors. The good accordance of our estimated results with data

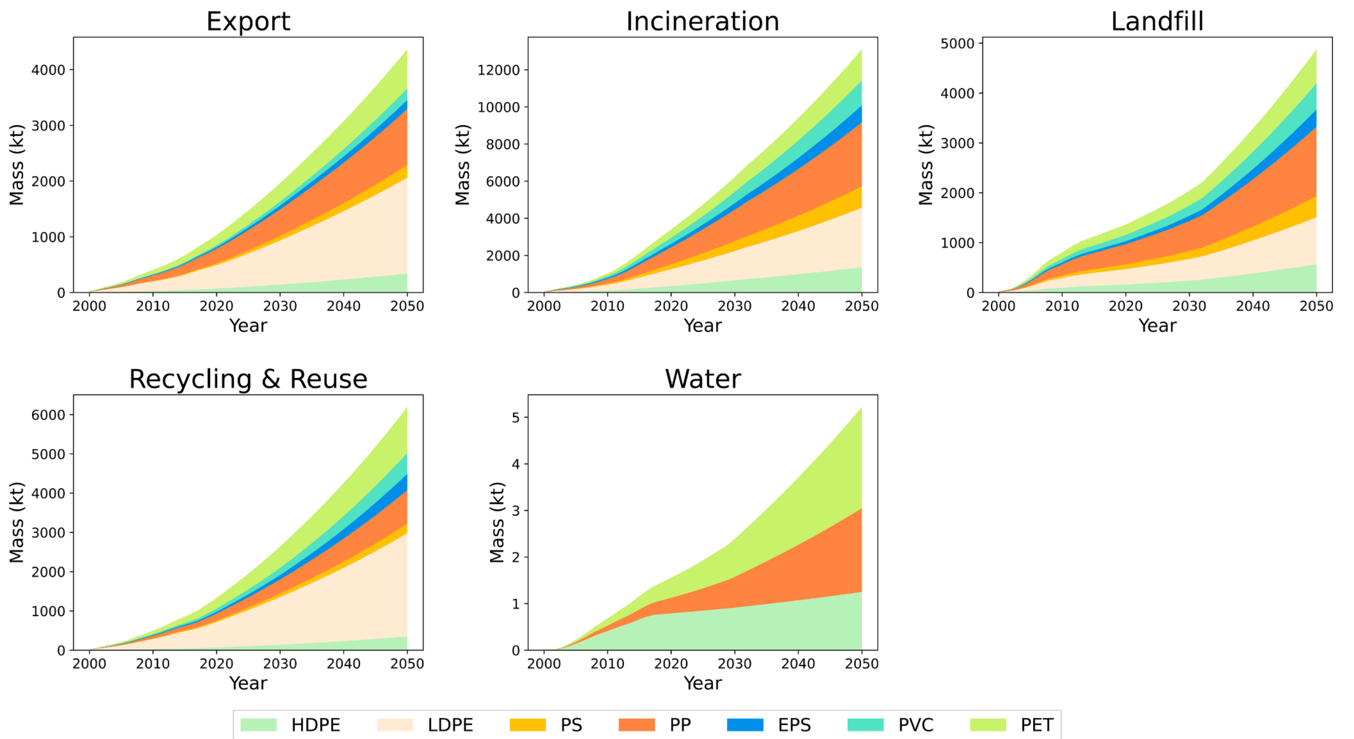

Fig. 6. Accumulation of plastic (in kt) in final sinks color coded by polymer type in Norway from 2000 to 2050. Graphs show the means of the probability distributions.

Table 2
The results of previous studies and databases in comparison with results of this study. The results were calculated for the same lifecycle stage and year as in the reference study.

Reference	Lifecycle stage	Polymers	Country	Year	Reference value	Estimate for Norway (this study)
(Kawecki et al., 2021)	Total POM	7 polymers	Europe	2016	90 kg/capita	110 ± 4 kg/capita
(Van Eygen et al., 2016)	Total POM	Plastic	Austria	2013	156 kg/capita	100 ± 4 kg/capita
(Kawecki et al., 2021)	Total stock	7 polymers	Europe	2016	465 kg/capita	530 ± 10 kg/capita
(Kawecki et al., 2018)	Total waste generation	7 polymers	Europe	2014	50 kg/capita	79 ± 5 kg/capita
(Van Eygen et al., 2017)	Packaging waste generation	Plastic	Austria	2013	35 kg/capita	32 ± 4 kg/capita
Table 13136 (SSB, 2022c)	Household separate waste collection	Plastic	Norway	2020	61 kt	67 ± 6 kt
Table 10514 (SSB, 2022b)	Agriculture waste generation	Plastic	Norway	2020	34 kt	28 ± 4 kt

collected by SSB reflects the reliability of the parameters, assumptions and the precision of our model in mapping out the plastic stocks and flows in Norway.

Several other studies used the MFA methodology to estimate the flows of plastic or plastic polymers in different European countries (Table 2). Kawecki et al. (2021) and Van Eygen et al. (2016) estimated per capita plastic consumption in Europe and Austria. While our estimated Norwegian consumption of 109 kg/capita in 2016 (population data from SSB (2022a)) was slightly higher than Kawecki et al. (2021)'s 90 kg/capita for Europe for the same year, it was still lower than the 156 kg/capita Van Eygen et al. (2016) calculated for Austria in 2013. The in-use stock of polymers in Europe was estimated at around 465 kg/capita in 2016 (Kawecki et al., 2021). According to our estimates, the in-use stock of plastics is about 530 kg/capita in Norway in the same year. The annual total plastic waste generation was estimated at around 37 Mt or 50 kg/capita in 2014 in Europe (Kawecki et al., 2018). We estimated a waste generation in Norway of 410 kt or 79 kg/capita in 2014. Van Eygen et al. (2017) estimated that 35 kg/capita of plastic packaging waste was generated. The estimated value for plastic packaging waste in Norway is about 32 kg/capita for the same year. Thus, the estimated quantity of consumption and waste generation in Norway are in good agreement with previous studies from different European countries.

4.2. Towards closing the loop of plastic polymers

While previous studies estimated global (Geyer et al., 2017) or European (Kawecki et al., 2021) production, consumption, and waste generation of plastics, this study estimated detailed flows of plastics for the main industrial sectors on a national level. The addition of more industrial sectors or product categories relevant to Norway, such as boats and fishing gear, allowed us to develop a framework enabling the inclusion of the regional and local activities essential for strategic planning to reduce plastic waste. The developed framework can easily be adopted by other countries for establishing a comprehensive plastic inventory based on their relevant industrial activities and waste management practices.

The overall recycling rate of all seven polymers from the nine industrial sectors is about 25% in Norway. Although this value is higher than the estimated global recycling rate of 9% (Geyer et al., 2017), it is much lower than the ambitious recycling targets set to be reached within the next few years. For instance, the European target is to recycle 50% of plastic packaging waste by 2025 (EC, 2018), and the same ambition exists for all plastic waste in Norway (Handelens Miljøfond, 2021). According to our estimates (Table S3) of all polymer types, LDPE (~70%), EPS (~60%), and PET (~60%) have the highest rate of separate collection from the waste stream followed by PVC (~50%), PP (~40%), HDPE (~35%), and PS (~15%). The high recycling rate of ~35% estimated for LDPE could be due to the high recovery and recycling of these polymers from plastic packaging and the agricultural sector, and for PET due to high recycling rates for certain packaging products, such as PET bottles which are separately collected in Norway. EPS and PVC have a recycling rate of around 20% which attributes to their recovery and reuse in the construction sector. While PP and HDPE packaging have a high rate of separate collection (both around ~30%), the overall recycling rate for these polymers is around 15% for both polymers due to their wide usage in many different industrial sectors and miscellaneous plastic products that are not properly collected or processed in the waste stream.

In the packaging sector, LDPE constituted ~40% of plastic POM with ~60% being separately collected from the waste stream in 2020. Foils make up the largest share of the separately collected packaging waste. If all the separately collected LDPE waste could be reused as a secondary material for new products in packaging, it would supply up to 60% of LDPE demand for packaging in 2021. LDPE is also used in agriculture and the available secondary material from packaging could satisfy the complete LDPE demand in agriculture in 2021. PET constitutes ~15% of POM packaging and ~25% of separately collected waste, with a separate collection rate of ~70%, the highest among all polymers. Drinking bottles constitute ~70% of PET packaging waste and have a separate collection rate of 92% (Infinitum, 2020), providing a clean and easily accessible fraction of secondary material in Norway. This secondary material could be used in the packaging industry again where by 2021, up to 75% of the demand for PET could be satisfied with recycled materials. Today, the demand for recycled PET (rPET) is higher than its supply. Considering that the EU set the target of using 30% recyclate in new drinking bottles by 2030 (EC, 2019), the growing rPET demand for drinking bottles will limit the application of rPET in other product categories. However, if the quality of rPET is not satisfactory for its application in drinking bottles, the reuse of rPET in other sectors, such as textiles, should be considered.

HDPE is a very versatile polymer with some applications in all nine industrial sectors. The majority is used in packaging, especially rigid packaging, such as shampoo bottles, cleaning supply containers, or soap bottles. Currently, only ~30% of HDPE packaging is separately collected. With HDPE being one of the most convenient polymers for recycling and reuse (Scranton Products, 2022), there is a huge potential to increase HDPE collection and their use as secondary material in the future. A possibility could be the introduction of a deposit return scheme for HDPE bottles alongside PET bottles that is already in place in Norway. If similarly high collection rates can be achieved, up to 15 kt of HDPE could be available in 2021 as a secondary material. Considering the potential reuse of HDPE containers, waste prevention strategies should also promote the refill and reuse of these containers where possible.

In the construction sector, EPS and PVC (~80% and ~60%, respectively) are the predominant polymers. Waste from the construction sector was assumed to have a collection rate of 100% (Kawecki et al., 2018), with the potential to serve as secondary material for new products. However, due to the long lifetime and the delayed release of these products, less material is becoming waste than what is required for new products in a given year. Assuming an average lifespan of 30 years for plastics used in the construction sector and a high recovery and recycling rate, to use all separately collected construction waste, the amount of plastic POM in the construction sector in 2020 would supply about 70% of both EPS and PVC demand in 2050.

The clothing and textile sector consumes up to 10% of all polymers considered in this study mainly PET as polyester, PP and in small amounts HDPE. While clothing is mostly made up of polyester, equal amounts of polyester and PP fibers are used in other textiles. Currently, only ~45% of clothing and other textiles are separately collected, meaning that 33 kt of synthetic textiles ended up in mixed waste and were incinerated in 2020. This presents an opportunity for increasing collection and recycling of textiles in Norway (Watson et al., 2020).

The detailed descriptions of the plastic polymer waste generation for the nine major industrial sectors allowed us to identify prospects for implementing circular strategies at inter- and intra-sectorial levels in Norway. The presented solutions from each industrial sector can be used as guidance for authorities to better implement or evaluate the extended producer responsibility programs that are in place in Norway. Moreover, the release of plastics to water could act as a primary source of microplastics in the aquatic ecosystems (UNEP, 2018). The release of fishing gear to the ocean and microplastics in cosmetics to the wastewater treatment plant are included in the model. An expansion of the model to include additional releases, such as littering of packaging, could identify private and industrial activities leading to the emission of macro and micro plastic polymers to the environment.

Despite the environmental and economic advantages of using plastic waste as secondary raw material for new products, the reuse of recyclates in new products could pose new challenges. There exist hundreds of different types of plastics and only seven of them were evaluated in this study. Separation of both plastic waste from municipal waste and plastic polymers by type is challenging for downstream actors. A high-quality secondary material can only be achieved with a high degree of separation and a low degree of impurities and/or cross-contamination among various polymer types. Currently, in Norway household waste is mostly separated by the consumer into specifically assigned bags and then collected by the municipality (Deloitte, 2019). In a few municipalities, the mixed plastic waste can be sorted by polymer types by using advanced technologies (IVAR, 2022; ROAF, 2022). Given the logistic and economic challenges associated with providing such infrastructure for waste treatment, better strategies should be in place to separate plastic products by polymer type before entering the waste stream. In addition, less variation in plastic types, especially for similar product categories, would reduce the challenges associated with recycling of mixed plastics and facilitate the production of high quality secondary raw materials (Klotz et al., 2022).

Another hindrance to the recycling of plastic is the presence of thousands of chemicals in many plastics that are added to the products to obtain or enhance various characteristics of polymers, such as durability, color, and plasticity. Some additive chemicals used in plastics are potentially concerning because of their adverse health effects (Wiesinger et al., 2021). The recycling of so-called chemicals of concern (CoC) and their unknown fate in new products can pose great risks to human health. There are some regulations in place regarding the use of food-contact materials in Europe restricting the use of plastic recyclates for food packaging (European Parliament, 2004). Hence, the recyclate from food packaging could be used safely in other short-lived plastic products with no human exposure potential (e.g., plastic furniture, plant pot, etc.). It should be noted that there is less scrutiny over miscellaneous products such as toothbrushes, kitchen utensils, and children's toys (Aurisano et al., 2021; Gerassimidou et al., 2022; Schlabach et al., 2021; Völker et al., 2022). For durable plastics used in construction, automotive, and EEE, closed systems of waste collection and recycling could ensure that the end-of-life products stay in a closed loop within the same industry in Norway.

Devising mitigation strategies to optimize the production and use of secondary raw materials requires reliable and precise data on the quantity and quality of waste collected at the municipal levels. Thousands of different product categories are classified by the harmonized commodity description and coding system (HS code) (International Trade Administration, 2022), which provides granular data on the number of products entering the market. However, data on waste are often incomplete for various sectors, unharmonized, overly aggregated, or lacking precision on waste characteristics. Unharmonized data compiled by different stakeholders, agencies, and authorities hinder effective strategic planning to maximize plastic recycling.

Addressing the challenges associated with the import and export of plastic waste destined for recycling is also a demanding task for authorities. According to the European law, the shipment of waste destined for disposal is prohibited to countries outside the EU (European Commission, 2022). However, the shipment for recycling of plastic packaging is allowed (European Environment Agency, 2021). A significant amount (~65%) of sorted plastic packaging waste in Norway is sent to other European countries for recycling. Although the Norwegian authorities have full oversight over the responsible treatment of plastic packaging waste sent to other European countries, the burden of Norwegian plastic waste could reduce the capacity of receiving countries to manage their own plastic waste. This, in turn could lead to the shipment of plastic waste generated in those countries outside of the EU (European Environment Agency, 2021). Moreover, the inconsistency in the quality and lack of information about the composition and/or origin of recycled plastics imported into Norway are major barriers for Norwegian industries to use recyclates in their products. Domestic processing and recycling of plastic waste enable Norwegian industries to have access to the necessary information to use recyclates in their new products. This calls for increasing recycling capability and capacity in Norway to ensure proper recycling and provide a safe stream of secondary material to be used in new products in Norway.

Further, the potential applications of secondary raw materials must be taken into consideration before setting recycling rate targets for products and devising future recycling strategies (Klotz et al., 2022). The evolution of each polymer flow to the waste stream from different industrial sectors provides valuable knowledge for policy makers to define purposeful targets of plastic waste collection and recycling in the future. These targets need to be adjusted to account for the current and future state of waste collection and processing at the national level. For instance, policies should focus on polymers or product categories and items for which the options of reuse and/or safe use of recyclates exist. The developed framework in this study enables the systematic classification of product categories based on the characterization of polymer type from each industrial sector, which can easily be adapted for other countries. This outcome provides an invaluable tool for policy makers and authorities by assisting them to meet their obligations under the UNEA (5.2) to identify (a) obstacles in reducing the plastic production, consumption, and waste generation and (b) opportunities to maximize the suitable reuse of secondary raw materials while minimizing the potential threat to human health and the environment.

For a successful transition to a circular economy for plastics, future mitigation strategies and waste management scenarios should further explore the impact of (a) internalizing the cost of waste treatment considering the lifespan, durability of products, and waste treatment options, (b) imposing an extra tax on virgin plastic or tax credits for recycled materials to incentivize the use of secondary materials, (c) regulating the price of secondary materials, and/or (d) designing products for recycling with respect to the presence of chemical additives and available technologies for collection and processing of plastic waste.

CRediT authorship contribution statement

Golnoush Abbasi: Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Marina Hauser:** Methodology, Software, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Cornelis Peter Baldé:** Conceptualization, Writing – original draft. **Evert A. Bouman:** Software, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The python code is available on zenodo (https://zenodo.org/record/7220273) including the database with the used data and reference where the data came from. The supporting information contains the remaining data.

Acknowledgements

This work has received funding from the Research Council of Norway under the project "PLASTCYCLE - Optimizing Resource Efficiency while Minimizing Recycling of Hazardous Chemicals in a Circular Economy" (Project No. 303182). We would like to thank Dr. Sina Lystvet from Grønt Punkt Norge for providing us with data and for giving feedback on the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107693.

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