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Design of sustainable supply chains for managing plastic waste: The case of low density polyethylene

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A R T I C L E I N F O

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A B S T R A C T

Plastic waste management presents a significant challenge that requires the integration of supply chain and sustainability principles. This study proposes a comprehensive supply chain model for plastic waste and management, specifically low-density polyethylene (LDPE), focusing on economic and environmental considerations. A model based on Mixed Integer Linear Programming (MILP) is developed to address the type of plastic waste management technology, their location through the United States East Coast and the effect of transitioning to an electrified transportation. The model determines plastic waste pyrolysis as the preferred technology to maximize profitability, and mechanical recycling combined with hydrogenolysis and hydrocracking to minimize the global warming potential (GWP). The mix of technologies for minimizing the GWP is highly correlated with the type of transportation, being desired to remove hydrogenolysis when electric trucks are introduced. This electrification of the transportation reduces the emissions by 23 %, but with an increase in the costs by 4 %.

1. Introduction

Plastic waste management is one of the most daunting challenges nowadays. The global plastic production is estimated to be nearly 400 million tons and to increase to over 1200 million tons by 2050 (Ellen-Macarthur-Foundation, 2016; Rochman et al., 2013). Most plastics are often discarded after their first use. Nonetheless, their functional characteristics remain intact (Geyer et al., 2017). This attribute gives potential for reuse and recycling. However, only 9 % of the total plastics produced in the United States is recycled, and 16 % is incinerated (Environmental Protection Agency et al., 2018). The remaining 75 % is disposed of into landfills and open dumps from where it can decompose and harm the ecosystem (Lebreton and Andrady, 2019). These landfilled plastics also result in estimated economic losses in the United States of $7.2 billion per year in market value and 3.4 EJ/y in embodied energy (Milbrandt et al., 2022). Recycling plastic waste to close the circular economy is, therefore, necessary from economic and environmental points of view (Cabernard et al., 2021; Law et al., 2020) with recycling rates over 80 % of the total plastic waste generation by 2040, according to the United Nations (United Nations News, 2023). Among the different polymers generated as plastic waste, low density polyethylene (LDPE) is the one with highest opportunities to be recycled. It is the one with highest share of production, 24 % of the plastic produced (Statista, 2023), and it can be easily sorted through mechanical methods since its density is significantly lower than other polymers (e.g. polypropylene, high-density polyethylene, poly-vinyl chloride) (Lange, 2021; Larrain et al., 2020).

Economic and environmental assessment of mechanical and chemical recycling of plastic wastes have sometimes considered plastic to be a zero cost raw material. However, collection and sorting have been demonstrated as critical contributors, accounting for up to 60 % of the final cost. Sorting is required in all recycling technologies, either mechanical, chemical, or thermochemical, to ensure a high conversion, better control and avoid damaging the catalysts. This sorting represents ~25 % of the costs and collection represents around ~35 % (Hernández et al., 2023). Collection has been evaluated in recent works demonstrating that the cost can double depending on the region when plastic is

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Nomenclature

Indices

k	Commodities (products or raw materials)
$p(k)$	products
$r(k)$	raw materials
n	Locations (supplier, facilities, and customer)
$s(n)$	supplier
$f(n)$	facilities
$c(n)$	customers
τ	Technologies
m	Transportation modes
l	Capacity level

Relational indices

$h(k,m)$	Commodities k that can be transported by mode m
$u(k,c)$	Commodities k that can be sold to consumer c

Decision variables

Binary variables

$x(k,n,n',m)$	1 if commodity k is transported from location n to n' through mode m
$y\tau l(f,\tau,l)$	1 if technology τ is established at location f operating at capacity level l

Continuous variables

$Q^{\mathscr{k}}(k,n,n',m)$	Quantity of commodity k moving from location n to n' through mode m
$Q^{treated}(r,f(n),\tau)$	Quantity of raw material r treated in a facility f using technology f
$Q^{\mathscr{p}}(p,f(n),c(n),m)$	Quantity of product p moving from location f to c through mode m
$Q^{\mathscr{r}}(r,s(n),f(n),m)$	Quantity of raw material r moving from location s to f through mode m

Parameters

$pr(p)$	Price of product p
$\tau Cost(\tau,l)$	Cost of installing technology τ of capacity level l
$_{m}\mathscr{C}ost$	Unit transportation cost per mile
$c\,\mathscr{C}ost(s(n))$	Collection cost at supplier node $s(n)$
$\gamma(r,p,\tau)$	The yield of technology τ for converting material r to producto p
$\delta(n,n')$	Distance between node n and node n'
$opt(\tau)$	Operating cost of technology τ
$cap(l)$	Capacity level
$\mathscr{e}^{p}Imp(p)$	Environmental gains from manufacturing products p
$\mathscr{e}^{\tau}Imp(\tau)$	Environmental impact from operating technology τ
$\mathscr{e}^{m}Imp(m)$	Environmental impact from transportation operating mode m
$w(\tau)$	Mass fraction of material sent to each technology τ
$GWP(\tau)$	Global warming potential of each technology τ

chemically recycled via pyrolysis (Ma et al., 2023). This cost of the supply chain can also limit some projects. Pyrolysis plants with capacities of nearly 200 kt/y have been proposed, but they have never been built, and the current largest plant has a size of 35 kt/y (Li et al., 2022). This critical role of collection has been determined by holistic environmental assessments and management-oriented studies that have highlighted the importance of regional-specific conditions (Bachmann et al., 2023). Supply chain design studies have remarked the influence of waste heterogeneity (Burgess et al., 2021; Rutkowski and Rutkowski, 2017) and dispersion in low-density population areas on the cost of collecting specific plastic wastes (Lombrano, 2009; Wong, 2010). In order to address this problem, computational studies have boarded the problem using different approaches. On the one hand, metaheuristic optimization techniques have been employed at municipal scale (Rada et al., 2013; Sumathi et al., 2008; Vu et al., 2019), On the other hand, mathematical optimization, based on mixed-integer linear programming (MILP), has been employed to design the supply chains (Santander et al., 2020) at a regional and national levels (Xu et al., 2017). By following this MILP approach, recent work on plastic upcycling has studied pyrolysis as a viable technology (Ma et al., 2023). The work determined the location of the collection center and the pyrolysis plant to be built in the Midwest region of the United States, but it misses the competitivity that other plastic management technologies (e.g., mechanical recycling, gasification, incineration or hydrogenolysis) can have with pyrolysis. The analysis of multiple technologies was presented in prior literature evaluating different alternative future scenarios with material flow analysis (Bachmann et al., 2023; Lase et al., 2023). The studies for Europe (Lase et al., 2023) and the U.S. management (Milbrandt et al., 2022) employed pyrolysis and mechanical recycling as the main contributors for treating plastic waste and giving a minor relevance to novel technologies like hydrocracking or hydrogenolysis. Furthermore, these studies based on material flow analysis did not provide where the plants should be located, and the logistics costs, which have been demonstrated as critical economic and environmental contributors.

In order to fill these gaps from material flow analysis studies and single technology MILP optimization framework, this work proposes a MILP optimization model to simultaneously select the optimal technology, location and its capacity for plastic waste management according to economic and environmental criteria. As an extension to previous works, we introduce novel (e.g., hydrocracking, hydrogenolysis) and conventional technologies (pyrolysis, mechanical recycling) with the aim of estimating the potential of implementing the novel ones. Furthermore, comparisons are provided for upcycling versus mechanical recycling, determining the economic and environmental potential of introducing those technologies and feasible combinations for profitability ensuring negative emissions. In this study, upcycling is referred to as refers to methods that convert plastic waste into new products of higher value. For the study, the United States east coast is selected, and the supply chain is evaluated, for both the conventional trucks, and electric trucks. This allows comparing two approaches for acting on the decarbonization of the overall plastic waste supply chain: by acting on the technology or by acting on the transportation, which is another question that have not been solved yet. In what follows, Section 2 presents a literature review of plastic waste management alternatives and formulations for design of supply chains for waste management. The methodology for designing the supply chain and analyzing the technologies used in each region is presented in Section 3. Section 4 presents the results, and Section 5 concludes the work.

2. Literature review

2.1. Literature review on plastic waste management technologies

Mechanical recycling is the most common recycling technology to post-consumer plastics. It consists of the sorting and recovery of the polymer based on physical methods. Since the polymer chains are not broken, it has low processing costs, but the polymer degrades, limiting the application of this technique between 2 and 6 times (Dogu et al., 2021). Due to polymer downgrading and the novel policies in China banning the acceptance of plastic from foreign countries (Wen et al., 2021), research interests on alternative technologies have emerge in the US and Europe. Among them, chemical and thermochemical technologies have been proposed due to their ability to recover polymers with intact properties called chemical recycling, or generate value-added products called upcycling. Chemical methods that combine solvents and antisolvents can be very effective at a laboratory scale (Poulakis and Papaspyrides, 1997; Walker et al., 2020), but no industrial-size facilities exist. Furthermore, chemical recycling usually involves toxic and carcinogenic compounds like toluene, which limits its implementation since the polymer recycled cannot be sold for some applications like food packaging (European Union, 2022). With higher quality products and easier to scale-up, thermochemical technologies have been developed at the industrial level (Plastic-Energy, 2021). Among them, pyrolysis is the most studied since it allows easy processing and can handle different plastic wastes (Li et al., 2022; Lopez et al., 2017). The process results in naphtha composed of paraffins, olefins, and aromatics. Among the three types of compounds, olefins are the most desired since they can be transformed into a wide range of products like lubricants, detergents or virgin monomers. The transformation into virgin monomers (e.g. ethylene and propylene) that are latter polymerized is known as chemical recycling (Gracida-Alvarez et al., 2019), whereas the conversion into higher valuable products like lubricants is known as upcycling (Fivga and Dimitriou, 2018; Larrain et al., 2020) Both alternatives for naphtha processing were compared by (Larrain et al., 2020) showing that pyrolysis followed by naphtha commercialization to refineries for value-added products can be more competitive than chemical recycling (Larrain et al., 2020). To generate added value, other thermochemical technologies and products have also been studied in the last few years. Due the ability of treating mix plastic wastes, gasification has been evaluated for the production of hydrogen (Al-Qadri et al., 2022; Lan and Yao, 2022) and methanol (Singh et al., 2022). Lan and Yao (2022) evaluated the economic feasibility of gasifying plastic wastes demonstrating the process to be competitive against green hydrogen production. As an alternative to hydrogen production, (Singh et al., 2022) evaluated the production of methanol from mix plastic waste obtaining lower minimum selling prices than for biomass-based methanol. Hydrothermal liquefaction (HTL) is the last thermochemical process able to treat mix plastic wastes since it does not involve catalysts that can be blocked and drop the yield. Since it does not require high temperatures, HTL was demonstrated to be more economically competitive than gasification (Hernández et al., 2023). Apart from these conventional technologies, recent studies have focused on the development of thermochemical catalytic processes. These technologies, operating at mild temperatures and employing hydrogen for breaking the polymers, have been demonstrated to be more sustainable than conventional technologies. Hydrocracking, which produces a commercial fraction of fuels, was estimated to be profitable at large scales, above 60 ktons plastic per year. The second, hydrogenolysis, is more profitable since it produces higher fraction of olefins that can be transformed in value-added products like lubricants (Cappello et al., 2022).

2.2. Literature review of formulations for the design of supply chains for waste management

Supply chain design and operations play a critical role in optimizing product lifecycle, ensuring cost-effectiveness, sustainability, and assessing risk (Chopra, 2019). Generally, for waste management, the large-scale and long-term impacts demand a proactive management method necessitating a sustainable objective. This is done by selecting the best treatment technologies and capacities, the locations of this technology, optimal waste collection and product distribution strategies, and optimal facility operations strategies. Mixed integer programming is recognized as a powerful tool for formulating and determining the aforementioned optimal decisions (Garcia and You, 2015). From a supply chain level perspective, some methods have focused on solving the supply chain design problem by exploring the optimal network configurations to achieve given objectives (Aviso et al., 2023; Castro-Amoedo et al., 2021) using a mathematical programming model to optimize plastic recycling networks, with an emphasis on maximizing the output of recycled plastic, minimizing the need for presorting, and diminishing dependency on landfills. Lim et al. developed a mixed-integer programming model designed to pinpoint the most cost-effective sorting and recycling strategies for plastic waste (Lim et al., 2023). Other works have combined technology to access the most cost-effective technology, and recent work on plastic upcycling has studied pyrolysis as a viable technology (Ma et al., 2023). Other studies suggest that pyrolysis could coexist with mechanical recycling to ensure sustainable plastic management (Bachmann et al., 2023; Lase et al., 2023). In our study, we have accessed other technologies that may present competitive economic and/or environmental advantages over pyrolysis.

Other approaches have explored optimal tactical and operational decisions for fixed supply chain designs. Mohammadi et al. developed models to optimize integrated tactical and operational decisions for waste to energy (Mohammadi et al., 2019), waste management combining technologies (Mohammadi and Harjunkoski, 2020), and organic waste (Mohammadi et al., 2021). In each work, they demonstrated the network's adaptability to changing market conditions.

From a multi-objective perspective, solutions explore tradeoffs between conflicting objectives and either present decision-makers with a frontier of optimal solutions or incorporate a policy to ensure decisions are amenable to stakeholders. Cristiu et al. (Crîstiu et al., 2024) assessed the tradeoffs in economic benefits and environmental impacts between incineration and pyrolysis for mixed plastic waste management in Northern Italy. Incineration is more profitable but results in greater CO_2 emissions, while pyrolysis achieves lower emissions at a reduced profit margin. It explores Pareto optimal solutions to identify a balanced approach to selecting technologies for sustainable waste management. Saif et al. (Saif et al., 2022) developed a dynamic optimization model for sustainable municipal solid waste (MSW) management, balancing economic gains, environmental impacts, and social benefits. It identifies conflicts among sustainability objectives through a case study, using Pareto optimal solutions to navigate these tradeoffs, suggesting a comprehensive approach to MSW treatment technology selection and network design. Ooi et al. (Ooi et al., 2023) developed a framework to analyze the impact of emissions trading schemes on municipal solid waste (MSW) management in Malaysia. Our study fills the gap in literature by considering multiple competing technologies (which has never considered) in the supply chain design for plastic waste. Specifically, the major contribution of our study includes: (i) addressing the supply chain network design for alternative plastic treatment technologies, encompassing both emerging and existing technologies; (ii) explore the impact of decarbonizing transportation on the supply chain network design, including technology and location choices; and (iii) exploring the achievable limits for the supply chain design by examining the trade-off choices between economic and environmental objectives. In the subsequent section, we will discuss the methodology employed in our study.

3. Methods

The simultaneous selection of upcycling technologies and supply chain design is formulated as a MILP problem. A MILP optimization approach is selected since the aim is to simultaneously decide about the type of management facility, its location and capacity, and the transportation methods employed. Selecting the type of management facility and the type of transportation requires to extend the formulation previously presented by Ma et al. (Ma et al., 2023). More details about the formulation are given in the SI. A summary of the methodology is sketched in Fig. 1, and a more detailed description is given in the following subsections.

3.1. Spatial distribution of waste

Plastic waste is generated heterogeneously throughout the counties and can involve centralized (e.g., industrial hubs) and dispersed (e.g., households) zones (Jones and Kammen, 2014). Evaluating the plastic waste generated by each industry requires a thorough analysis of all the

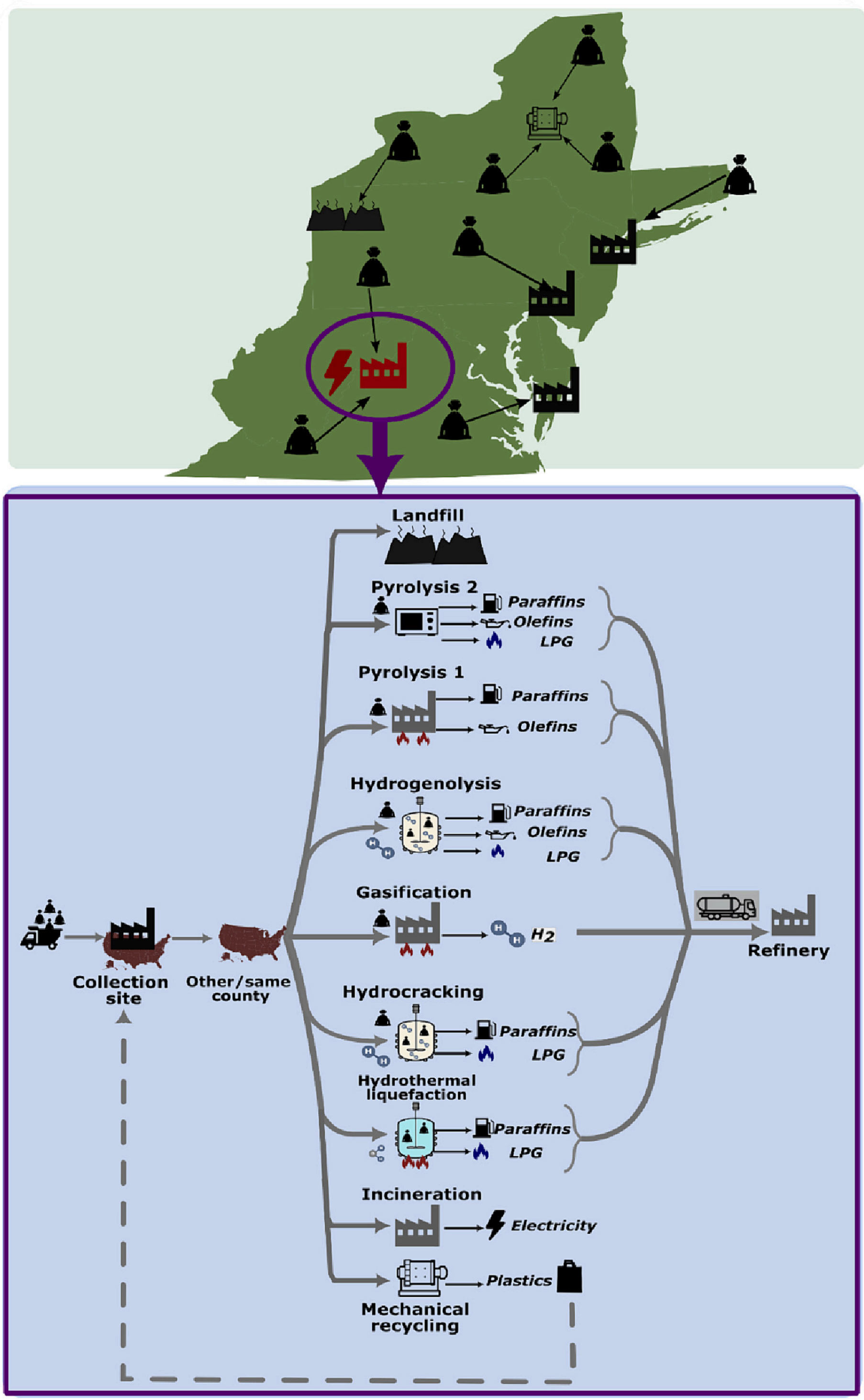

Fig. 1. Summary of the processes considered and integration into the supply chain design.

processes involved in each of them. For simplicity, each county's plastic waste is estimated based on the generation per inhabitant in the U.S, 221 kg/person·y (OECD, 2023), multiplied by the fraction of LDPE in the U.S., 24 % (Statista, 2023). This contribution is computed by multiplying the average plastic waste per person by the county's population. The waste collection cost in each county is determined based on a surrogate model generated from the data obtained from Lombrano's work (Lombrano, 2009). It should be noted that the aforementioned data was for Italy in 2010, and in developing the surrogate model, the differences in Gross Domestic product (GDP) between Italy and the United States, as well as the cumulative inflation from 2010 to 2022 were considered. This correction with the GDP is considered as a general indicator to address those economic differences (cost of driver of the trucks, fuel costs) between both countries. See more details in the Supplemental Information (SI). The model has been used to estimate the collection cost in all counties of the east coast located between meridians −72°W and −79°W; and latitudes 38.5°N and 42°N in the states of New York, Connecticut, Pennsylvania, Virginia, Delaware, New Jersey, and Maryland. These counties are selected due to their proximity to all the refineries on the east coast where naphtha can be post-processed into value-added products.

It is assumed that all waste from each county is sent to a collection site located in the center of each county. In the model, the material flow in the supply chain starts at the collection facilities, as shown in Fig. 1. The collected plastics are then transported to processing facilities, where they are transformed into products for refineries, recycled as plastics, or burned for electricity generation. These products are then transported to their final destinations, which can be either cities or refineries. The cities receive electricity or recycled plastic, while the refineries use the products from the transformation technology as a substitute for crude oil.

3.2. Description of the plastic waste treatment technologies

This study examines nine distinct technologies for the treatment of plastic and compares their outcomes to those of the three conventional methods, namely incineration, mechanical recycling, and landfilling. Below we provide a description of each technology, with additional information of the fluxes, operating expenses (OPEX) and capital expenses (CAPEX) available in the SI.

- ***Pyrolysis 1*** is using a fluidized bed reactor (Zhao et al., 2020), where naphtha is produced and transported to the refinery. The value of the naphtha is based on the percentage of olefins (prices between \$0.8–1.5/kg) (Chemanalyst, 2023) and paraffins (price as gasoline ∼ \$0.5/kg)(U.S. Energy Information Administration, 2023).
- ***Pyrolysis 2*** employs an intensified modular pyrolysis reactor based on microwave heating, namely an electro-upcycling technology (Selvam et al., 2023). The integrated process produces a mixture of paraffins and olefins, where a fraction is in the C3-C4 range. The C3-C4 fraction is assumed to be liquid petrol gas that is transported to a refinery for final distribution.
- ***Gasification*** at high temperatures with steam producing syngas (a mixture of hydrogen and CO) (Lopez et al., 2018). A water-gas-shift reactor can increase the hydrogen content of syngas. After the water-gas-shift reactor, a pressure swing adsorption system is utilized to obtain high purity hydrogen. This hydrogen is sold to refineries for \$2.1/kg (Hernández et al., 2023).
- ***Hydrothermal Liquefaction*** produces a liquid mixture of hydrocarbons, mainly composed of paraffins, operating at mild temperatures and high pressures with water. The mixture of hydrocarbons obtained is sold to refineries for postprocessing at a cost given by the price of paraffins (Jin et al., 2020).
- ***Hydrocracking*** is a novel catalytic technology that uses hydrogen and convert the plastic waste in naphtha, mainly composed of paraffins, that is transported to the refinery for post-processing (Liu et al., 2021).
- ***Hydrogenolysis*** employs high-pressure hydrogen and mild temperatures to produce a mixture of paraffins and olefins which are sent to refinery for separation and post-processing (Hernández et al., 2023).
- ***Mechanical recycling*** is the most established technology for waste plastic recycling (Larrain et al., 2021). The plastic obtained as a product has degraded properties, so in our modeling process, it is assumed that the value is 0.5 times the one of virgin LDPE (Dogu et al., 2021). This assumption is based on a conservative value of considering two recycling cycles.
- ***Incineration*** is another widespread technology where plastic is utilized to produce energy (Bora et al., 2020). The electricity is sold directly to the network, whose transport costs are assumed to be negligible.
- ***Landfill*** is the most extended management of plastic waste currently. The costs involved in landfills follow the Environmental Protection Agency report (U.S. Environmental Protection Agency, 2015), assuming a tipping fee. The emissions in the operation are assumed to be the one reported in Ecoinvent for managing waste polyethylene in open dumps.

3.3. Model formulation

The model is formulated as a multi-objective Mixed integer Linear Programming (MILP), which consists of maximizing profit and minimizing the global warming potential (GWP). Below, we start with model descriptions, after which we state the assumptions and the mathematical model build up (objective functions and constraint). More details, including the model formulation, are given in the SI.

3.3.1. Model description

The study addresses a three-tiered supply chain problem involving the transportation of commodity k which is either raw material or products. The commodity includes the raw materials $r(k)$, which is in this case plastic, and the products $p(k)$ that can be manufactured from plastics. The formulation defines the supply chain network as a directed graph consisting of nodes and arcs. These nodes are further broken down into subsets based on the supply chain echelon. Specifically, the network encompasses three echelons interconnected by transportation nodes: collection sites $s(n) \in S \subset N$, potential facility locations $f(n) \in F \subset N$, and customer location $c(n) \in C \subset N$. Raw materials $r(k)$ are sent from collection sites to facility locations which selects the optimal technology to transform the raw materials to products $p(k)$. Depending on what the final products are, they are either sent to the refineries or cities. The objective is to determine optimal facility locations, selected technology (ies) on these facilities, and the operational capacities of the selected technology that optimizes the distribution of commodity k.

3.3.2. General aspects of the model

The model is formulated as a MILP problem. The formulation defines the supply chain network as a directed graph consisting of nodes and arcs. The nodes are further broken down into subsets based on the supply chain echelon. We have three echelons connected by the transportation nodes: the collection sites, the potential facility locations, and the customer locations. The following assumptions are made:

1. The population of the county determines the capacity of the plastic collection facilities. The collection centers are located at the geocentric point of each county. In the selected region, 133 counties on the east coast of the United States are involved. It is assumed that each collection center sells the plastic waste at a price given by the collection costs as defined in Section 2.1.
2. A set of 200 potential locations for plastic management technology is considered. This set addresses the possible capacity for each technology, cost, and emissions information. The operating costs, capital cost, and emissions of the technologies defined in Section 2.2 have been determined utilizing TEA and LCA, and they have been reduced to parametric and piecewise linear models. See more details in the SI
3. The consumers consist of cities and refineries. The refinery locations are considered according to Oil-Refinery-Watch (Oil Refinery Watch.org, 2023) while the coordinates of the cities are taken as the center of each county. It should be noted that products from depolymerization technology are sent to the refinery nodes and mechanical recycling products are sent to the cities.
4. The transportation choice depends on the commodity type and the transportation cost depends on the weights of the commodity. The costs and emissions for the transportation activity are specified by the distance traveled and the type of product transported. Electricity is assumed to be directly used by the network. See more details in the SI.

3.3.3. Model development

The model consists of the objective functions and the constraints. In what follows start with a compact formulation of the problem which is then followed by the descriptions of each of the objectives.

3.3.3.1. Compact formulation. The problem is abstracted as a bi-objective problem including the profit and global warming potential (GWP). This is adapted as follows:

$$min\{-Profit, GWP\}$$

s.t. :

Supplier capcity limitations

Facility locations selection

Technology choice limitations

Technology capacity limitations

Transportation mode and capacity limitations

The objective consists of two parts which are further explained in the next subheadings.

- *Supplier capacity limitation* constraints ensures that only selected suppliers can transfer plastics and the amount that can be transferred is limited by the capacity of the supplier node. It should be noted that this capacity is estimated based on the county population.
- *Facility location selections* ensure that the facilities that are selected are the only ones that can receive raw materials as well as the ones where technologies can be established.
- *Technology choice limitations* the manufactured products solely depend on the technologies selected. And only one technology can be selected for every location.
- *Technology limitations* ensure that we cannot produce beyond the selected capacity of the available technology.

Commodities are transported by trucks; each commodity has the mode of truck that can be used for its transportation and each mode of transportation has a limited capacity. The constraint ensures that the right transportation mode is used for each commodity and the amount each truck can take is limited by its capacity.

3.3.3.2. Economic objective. The economic objective corresponds to the monetary gains from operating the supply chain and the plants. This is computed as the difference between the sales revenue and the cost incurred. As shown in Eq. (1), the economic objective consists of two parts:

$$Profit = Revenue - TotalCost \tag{1}$$

Revenue from sales of products is calculated in Eq. (2). $\mathcal{Q}(p, f(n), c(n), m)$ is the quantity of products from facility $f(n)$ to consumer $c(n)$ by transportation mode m; and $\wp r(p)$ is the price of products p.

$$\mathrm{Revenue} = \sum_{\substack{p \in P \\ m \in M \\ (p,m) \in h(p,m) \\ f(n) \in F \\ c(n) \in C \\ (p,c) \in u(k,c)}} \mathcal{Q}(\mathrm{p}, \mathrm{f(n)}, \mathrm{c(n)}, \mathrm{m}) \times \wp \mathrm{r(p)} \tag{2}$$

The total cost is given as the combination of cost incurred in the opened facilities and the cost of transportation from a node (n). This is expressed in Eq. (3)

$$TotalCost = \sum\nolimits_{f(n)} cap\mathscr{C}ost(f(n)) + op\mathscr{C}ost(f(n)) + \sum\nolimits_{n} trCost(n) \tag{3}$$

The capital cost is the cost incurred for installation of a given technology τ operating at a level l in a facility $f(n)$. This is expressed in Eq. (4), the integer variable $y\tau(f(n), \tau, l)$ is 1 if facility $f(n)$ operates technology τ at capacity level l or 0 otherwise; $\tau\mathscr{C}ost(\tau, l)$ is a parameter that expresses the cost of installing the technology τ of capacity l.

$$cap\mathscr{C}ost(f(n)) = \sum\nolimits_{\substack{\tau \in \mathscr{T} \\ l \in L}} y\tau(f(n), \tau, l) \times \tau\mathscr{C}ost(\tau, l) \tag{4}$$

$$\sum\nolimits_{\substack{\tau \in \mathscr{T} \\ l \in L}} y\tau(f(n), \tau, l) \leq 1 \forall f(n) \in F \tag{4a}$$

It should be noted that Eq. (4a) ensures technology limitations in terms of both number of operatable technologies on a facility and the capacity level of the operating technologies in a given facility.

The second term in the total cost is the operating cost which is expressed in Eq. (5). This has two parts the collection cost from suppliers and the cost of operating a given technology. The collection cost from suppliers is expressed in Eq.(5a) as a product of the quantity of plastic collected from each supplier and the unit cost of collection. $\mathcal{Q}(r, s(n), f(n), m)$ is the quantity of raw material transferred from supplier $s(n)$ to facility $f(n)$ through transportation mode m. Following that, Eq.(5b) constraints the raw materials treated to the selected facility capacity, $Q^{treated}(r, f(n), \tau)$ is a variable that expresses the quantity of raw materials r treated by the facility $f(n)$, using technology τ and Eq. (5c) expresses the cost of operating an installed technology τ on a facility $f(n)$. The other Eqs. (5d)–(5e) expresses the mass balances at the operating facility locations.

$$OpCost(f(n)) = col\mathscr{C}ost(f(n)) + opTech\mathscr{C}ost(f(n)) \forall f(n) \in F \tag{5}$$

$$col\mathscr{C}ost(f(n)) = \sum_{\substack{r \in R \\ m \in M \\ (r,m) \in h(r,m) \\ s(n) \in S}} \mathcal{Q}(r, s(n), f(n), m) \times c\mathscr{C}ost(s(n)) \forall f(n) \in F \tag{5a}$$

$$\sum\nolimits_{\substack{r \in R \\ \tau \in \mathscr{T}}} Q^{treated}(r, f(n), \tau) \leq \sum\nolimits_{\substack{\tau \in \mathscr{T} \\ l \in L}} y\tau(f(n), \tau, l) \times cap(l) \forall f(n) \in F \tag{5b}$$

$$opTech\mathscr{C}ost(f(n)) = \sum\nolimits_{\substack{r \in R \\ \tau \in \mathscr{T}}} Q^{treated}(r, f(n), \tau) \times opt(\tau) \forall f(n) \in F \tag{5c}$$

$$Q^{treated}(r, \mathrm{f}(n), \tau) = \sum\nolimits_{\substack{s(n) \in S \\ m \in M}} \mathcal{Q}(r, s(n), f(n), m) \forall r \in R, f(n) \in F, \tau \in \mathscr{T} \tag{5d}$$

$$\sum_{\substack{c(n) \in C \\ m \in M \\ (p,c) \in u(p,c)}} \mathcal{Q}(p, f(n), c(n), m) = \sum\nolimits_{r \in R} Q^{treated}(r, f(n), \tau) \times \gamma(r, p, \tau) \forall f(n) \in F, p \in P \tag{5e}$$

The final component of the total cost is the transshipment cost from a node. This is expressed as the product of the cost of the commodity transported, the distance between the nodes and the unit cost of shipment per miles as expressed in Eq. (6).

$$\mathrm{trCost(n)} = \sum_{\substack{\mathrm{k} \in \mathrm{K} \\ \mathrm{n}' \in \mathrm{N} \\ \mathrm{m} \in \mathrm{M}}} \mathcal{Q}(\mathrm{k}, \mathrm{n}, \mathrm{n}', \mathrm{m}) \times \delta(\mathrm{n}, \mathrm{n}') \times m\mathscr{C}\mathrm{ost}$$

$$\forall((k, m) \in h(k, m)); (\{(s(n), f(n')), (f, c)\} \in (n, n')) \tag{6}$$

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3.3.3.3. Environmental objective. The environmental objective function corresponds to the minimization of the Global Warming Potential (GWP) obtained from a system expansion LCA performed on the supply chain. The emission factors are determined following the Traci method (Bare, 2011) and the Ecoinvent v3.9 database, see more details on the fluxes and factors in the SI. The system expansion approach is used since it allows determining the decarbonization potential of utilizing plastic waste and it can be employed for comparing all technologies under the same functional unit, LDPE waste to be treated. The boundaries of the system are presented in Fig. 2. In the calculation of the emissions with this approach, the following terms are included:

- Activity Impact: The emissions generated by all the supply chain's processes. The collection of the plastic waste and its sorting, the emissions generated by technologies transforming raw materials to products, utilities in each of the technology options, and the emissions due to transportation of the raw materials and products.
- Product substitution: The emissions avoided by substituting the products obtained by fossil-based products. For having a common framework of comparison, all the products are substituted, and the emissions are reported per kg of LDPE waste fed into the optimization model.
- Diversion: This term diverts includes the avoided emissions by diverting the LDPE waste from the business-as-usual scenario to the novel technologies implemented.

From this, we calculate the GWP is expressed in Eq. (7) as a combination of the aforementioned terms.

$$GWP = activityImpact - subEnvImp - Diversion \tag{7}$$

The activity impact can be divided into two terms the activities involved in transformation process - which includes the collections and emissions from technologies in the production stage - and the activities in the transportation from one node to the other. This is expressed in Eq. (7a).

$$activityImpact = \sum_{f(n)} prodImp(f(n)) + \sum_{\substack{n \in N \\ n' \in N}} trnsImp(n, n') \tag{7a}$$

The production impact encompasses the Global Warming Potential (GWP) resulting from the utilization of technologies, is expressed in Eq. (7). This is computed as the unit impact attributed to each technology $eImp(\tau)$ multiplied by its corresponding activity level. In each facility, the activity level is represented by the quantity of material treated $Q^{treated}(r, f(n), \tau)$.

$$prodImp(f(n)) = \sum_{\substack{r \in R \\ \tau \in \mathcal{T}}} Q^{treated}(r, f(n), \tau) \times e^{\tau}Imp(\tau) \forall f(n) \in F \tag{7b}$$

The transportation impact is computed as the GWP from moving commodities across nodes in different echelons. This is depicted in Eq. (7c). Two modes of transportation are considered depending on the use. Conventional trucks use gasoline as fuel, while electric trucks are charged. Under each mode of transportation there are three truck types for each mode of transportation:

Box trucks: These are mainly used to transport solids, and they

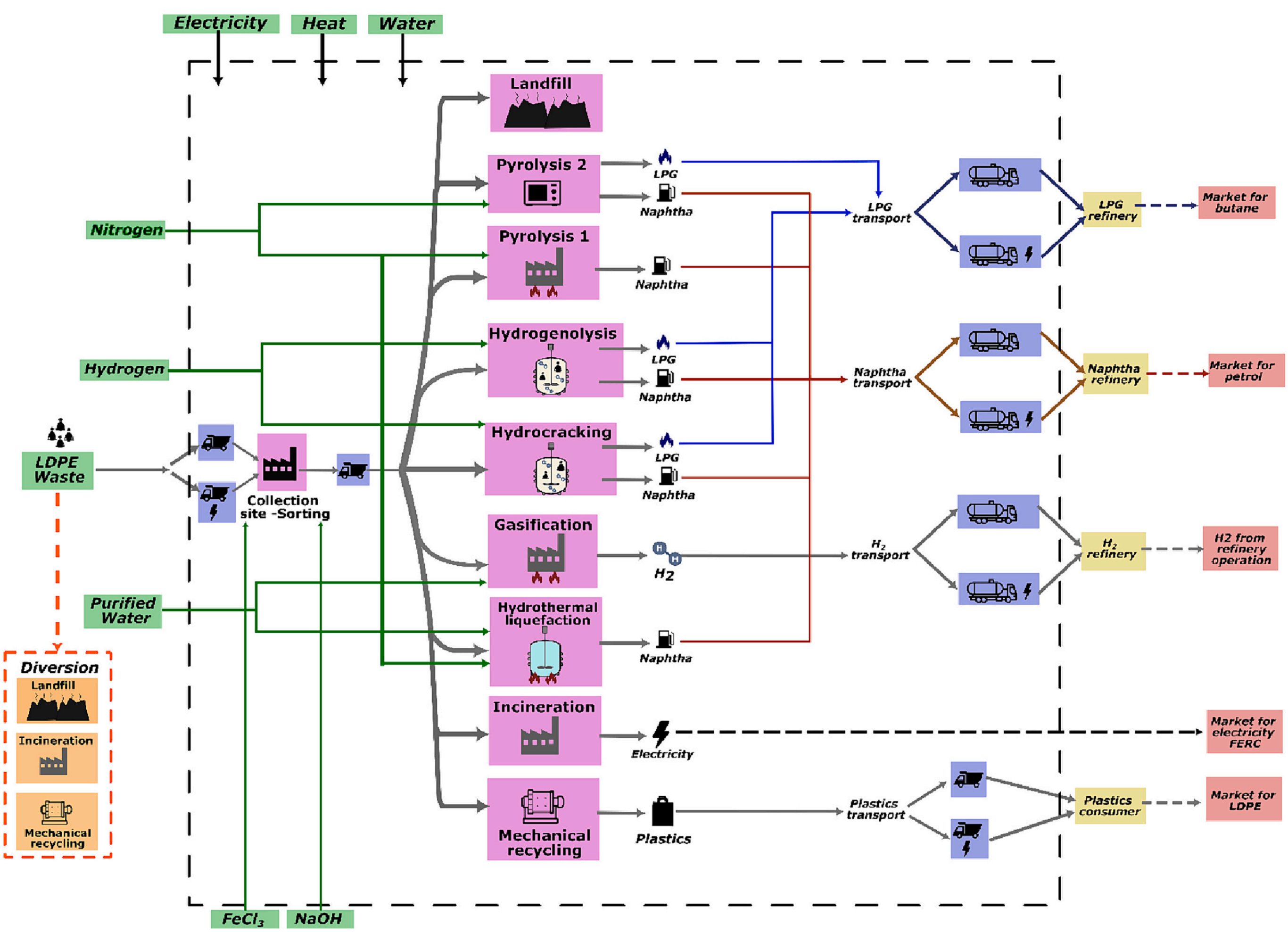

Fig. 2. Boundaries considered in the LCA.

usually have sizes of around 16 to 20 metric tons; see example in the SI. Thus, these trucks are assumed to have the emissions of a Lorry between 16 and 32 metric tons, as reported by Ecoinvent for the US. This mode of transportation is considered for transporting the plastics across nodes (suppliers to facilities and facilities to customers).

Tank trucks: These trucks can transport liquids (e.g., Olefins, Naphtha), and they have sizes of around 38 cubic meters, according to the estimation obtained in the SI. These trucks are assumed to be tanks with sizes above 32 metric tons from Ecoinvent.

Gas Tank trucks: The gas trucks are similar in design to the normal gas tank trucks with a maximum volume of 4 cubic meters (Amos, 1998), so they are taken as lorry of sizes from 3.5 to 7.5 metric tons from Ecoinvent.

The emissions for the three types of trucks with gasoline as fuel have been taken from the Ecoinvent v3.9 database, with the search performed as defined for each. The estimation of the emissions of electric trucks is determined by correcting the emissions with a factor for the energy consumed by each type of engine with the energy consumption reported in the work of (Fan et al., 2019) and the ratio of the emissions generated for producing the same amount of energy with renewables (assumed as photovoltaic energy) and gasoline, see more details of the calculation in the SI.

$$\mathrm{trnsImp}(n,n') = \sum_{\substack{k \in K \\ m \in M}} Q^{\ell}(k,n,n',m) \times e^{m}\mathrm{Imp}(m) \times \delta(n,n') \forall (n,n') \in (N \times N) \tag{7c}$$

The second term of Eq. (7) involves the product substitution; this is computed with Eq. (7d) as the products the quantity of products and the substitution gain for manufacturing product.

$$subEnvImp = \sum_{\substack{p \in P \\ f \in F \\ c \in C \\ m \in M}} Q^{\prime}(p,f(n),c(n),m) \times e^{p}Imp(p) \tag{7d}$$

The diversion term is assumed to be a constant value computed as the total waste in the region multiplied by the contribution of each technology to the GWP. see Eq. (7e). This contribution is computed with the percentage of mass treated by each technology currently in the US: 9 % recycled mechanically, 16 % incinerated and 75 % landfilled (Environmental Protection Agency et al., 2018).

$$Diversion = \sum_{\tau \in T} w(\tau) \times GWP(\tau) \times \sum_{\substack{p \in P \\ f \in F \\ c \in C \\ m \in M}} Q^{f}(p,f(n),c(n),m) \tag{7e}$$

3.4. Scenario analysis

The MILP optimization problem has 1,585,877 variables (186,540 binary variables and 1,399,337 continuous variables) and 2,101,370 equations, and it is solved using CPLEX in GAMS v.33. The developed supply chain model generated is used to analyze various scenarios through multi-objective optimization with two objective functions, economic (ECO) and environmental (ENV). Epsilon-constraint method (Marler and Arora, 2004; White, 1986, 1983) is employed for determining the intermediate tradeoffs between both objectives. This is implemented following the procedure outlined in (Badejo and Ierapetritou, 2022) The multi-objective optimization is solved for case studies: evaluating two transportation methods - conventional fuel vehicles (CON) versus electric vehicles (ELE), and limitations in the fraction sent to mechanical recycling. Reports have shown that plastic sent to mechanical recycling significantly degrades its properties. In the worst-case scenario, this plastic can be only recycled twice (Dogu et al., 2021; Uekert et al., 2023). Considering this limitation, in this scenario only 50 % of the collected plastic can be mechanically recycled. When limitations are considered, the acronym is defined as (MRL) and without limitations, the system is named as no-constraints (NC). Furthermore, opportunities due to technological development are evaluated including a case where only available technologies at large scale (AVL) are included. The cases employed and their acronyms are described in detail below:

Scenario 1 (*CON-NC*): The focus lies in solving the supply chain performance with conventional trucks. The multi-objective optimization is carried out between economic (ECO-CON-NC) and environmental (ENV-CON-NC) objectives for determining the network topology without imposing constraints on plastic recycling.

Scenario 2 (*ELE-NC*): This second case evaluates the impact of transitioning transportation fleets substituting conventional trucks fueled with diesel by electric trucks. As in previous case, multi-objective optimization is carried out between economic (ECO-ELE-NC) and environmental (ENV-ELE-NC) objectives.

Scenario 3 (*CON-MRL*): Employs the multi-objective optimization to identify intermediate solutions including limitations in the number of times plastics can be recycled mechanically. The worst case scenario limits the recycling twice so that only 50 % of the collected plastic can be mechanically recycled. In this case conventional trucks are used as transportation options.

Scenario 4 (*ELE-MRL*): Similar to CON-MRL scenario, this case focuses on the impact of using electrical transportation fleets. The electric trucks are selected for transportation, with an added constraint on the allowable number of plastic recycling cycles: 50 % of the collected plastic can be mechanically recycled. The resulting MILP is solved to identify generate the Pareto frontier.

Scenario 5 (*AVL-MRL*): In this scenario, we exclusively incorporate industrially available technologies (Pyrolysis, incineration, gasification, HTL, and mechanical recycling), alongside conventional transportation options, within a multi-objective problem framework. In this case the maximum amount of plastic that can be sent to mechanical recycling is also limited to 50 %. The primary objective is to establish a comparative basis for assessing viability against the two previous scenarios.

4. Results and discussion

4.1. Results with single objective economic and environmental optimizations

The solution of the MILP optimization determines the technologies and its location in the East Coast of the United States. In economic optimizations (ECO-CON-NC and ECO-ELE-NC), only Pyrolysis-2 is selected as the conversion technology. This technology was selected because it produces olefins, a highly valuable product that can be transformed into multiple end-products like aldehydes, polyolefins, surfactants, and lubricant oils. With conventional transportation, a total of 27 facilities are selected; meanwhile, in the implementation of electric trucks, a more decentralized production is preferred, with 28 facilities, since the electric trucks increase the cost of transportation, see Fig. 4. However, neither the facility distribution nor the economics (only a reduction of 9 % of the profit) change significantly, suggesting that fleet electrification can be gradually implemented independently of installing depolymerization technologies from an economic point of view. The GWP of these cases is 282.42 MT_{CO2}/y for ECO-CON-NC and 211.20 MT_{CO2}/y for electric vehicles for all the counties evaluated. In transportation, emissions are mostly reduced at the intercounty level, emphasizing the need for additional investigation to link the collection of waste at individual counties with the findings presented in this study.

However, the main contributor to the emissions is the process operations, see Fig. 3. Although Pyrolysis-2 employs electricity, it contributes at least 81 % of the emissions of the overall supply chain since the process consumes more energy in washing, sorting, and depolymerization than in the collection. Apart from the emissions generated, the system expansion approach determines the credits and decarbonization potential. The diversion of plastic waste from landfills represents 29 % of the emissions being avoided by decarbonization (versus 71 % of product substitution). Diversion represents less contribution than product substitution since the most abundant management technique, landfill, has low emissions in the processing. However, landfills do not generate any value from the plastic (plastic substitution), which highlights the current need to implement plastic waste recycling and conversion technologies. The last interesting analysis of the breakdown of emissions provided in Fig. 3, B) shows that collection from households to the collection facilities corresponds to greater environmental impact than the transportation from the collection facilities to the processing facilities or refineries. Although this work and other works (Bachmann et al., 2023) have focused on the country or even planetary levels, the main issue for emissions reduction from a management point of view is at a municipal level.

Minimizing the GWP selected only mechanical recycling as the conversion technology for the ECO-ELE-NC scenario (29 facilities) and mechanical recycling (99 % of the plastic waste and 24 facilities) combined with hydrocracking (1 % of plastic waste and 1 facility) in the ENV-CON-NC scenario. This change in the distribution of the plants indicates that the technologies introduced are highly connected to the electrification of the collection fleet. This is highly relevant if policies are to be developed for decarbonizing plastic waste management since incentives for transportation can also decarbonize waste management and should be considered. The reduction of emissions by electrification is 23 % compared to conventional transportation. However, like economic optimization, most emissions are generated by the process (at least 76 %). Analyzing the credits in these cases, product substitution is higher than plastic diversion (−273.7 MTCO2/y versus −24.88 MTCO2/y), which shows the importance of selecting adequate technology in each case. The substitution of LDPE is higher than that of other chemicals like gasoline or oil. In both environmental objectives, the economic results do not demonstrate profitability (−$1.58 Billion/y to -$15.56 Billion/y) since mechanical recycling generates a product of lower value, see Fig. 2. The lower value is due to the degradation of LDPE, which was assumed to be cheaper (a factor of 0.5 in the value). However, this degradation has not been included in the environmental function.

A worst-case scenario has been evaluated to evaluate the role of the degradation of LDPE in mechanical recycling, imposing a maximum of 50 % of LDPE waste sent to mechanical recycling. Two cases were studied using the multi-objective optimization: conventional and electrical transportation. In both cases, the economic objective suggests a combination of Pyrolysis-2 with mechanical recycling. When minimizing the GWP, the case with conventional transportation selects mechanical recycling (50 % of the plastic waste) together with hydrocracking (33 % of the plastic waste) and hydrogenolysis (16 % of the plastic waste); meanwhile, with electric transportation, the technologies selected are mechanical recycling and hydrocracking, 50 % each; see Fig. 4.

The differences between both cases, ENV-CON-MRL and ENV-ELE-MRL, depend on the technologies involved and their products. Hydrocracking produces a lower fraction of petrol gases as a byproduct than hydrogenolysis, which emits more CO_2 than transporting the naphtha. As a result, hydrocracking is only selected as an alternative to mechanical recycling with electric trucks, and the emissions are governed by the products. In this case, the emissions are −16.17 MTCO2/y with fewer but bigger plants (26 for mechanical and 21 for hydrocracking) preferred (different from the economic function since our aim here is to minimize the GWP). On the other hand, by minimizing the GWP with diesel trucks, the emissions are 59.41 MTCO2/y, and hydrogenolysis is introduced as an alternative technology. In this case, a higher number of plants (dispersed facilities) is preferred. 24 plants are for mechanical, 21 for hydrocracking, and 12 for hydrogenolysis. Since the distance to the refinery is a major factor in transportation costs, a comparison of the distribution of plants with the distance to the closest refinery is given in Fig. 5. It shows mechanical recycling to be located in remote locations and thermos-chemical technologies to be located near the refineries. In the worst case, thermo-chemical technologies are not recommended to be further than 55 miles. This recommendation is useful from a refinery point of view since it provides the region up to which plastic can be supplied to the refinery. These regions are selected for economic (ECO-CON-MRL) and environmental, (ENV-CON-MRL), objective functions so they are prompt to be influenced by the refineries under any policy implemented by the governments. On the other hand, in remote regions environmental objective tend to select mechanical recycling (usually managed by recycling companies) and economic objectives select pyrolysis. These remote regions are therefore expected to have a competition between refineries and mechanical recycling plants. In these regions, regulations developed by the governments will play a significant role in the technologies to be installed. Apart from the comparison between thermochemical and mechanical recycling, the analysis of the mean distance also shows hydrogenolysis to be nearer to the refinery than hydrocracking since it produces higher fraction of gas product, which leads to higher emission due to transportation. Besides comparing technologies, the economic and emissions breakdown of the minimization of the GWP is reported in Fig. 3. The is higher ($4.23 Billion/y versus $-0.57 Billion/s) with conventional transportation since transportation costs are reduced, and a technology like hydrogenolysis, which generates more valuable products (olefins), is selected.

4.2. Analysis of the results obtained in the Pareto set of solutions

We studied the multi-objective optimization problem for three systems and compared the results obtained in Fig. 6A). The three systems of interest are (1) CON-MRL: all technologies using conventional modes of transportation; (2) ELE-MRL: all technologies with electrical vehicles; and (3) AVL-MRL: only industrially available technologies (Pyrolysis-1, HTL, gasification, incineration, landfill, and mechanical recycling) are considered with conventional transportation. In all three cases, there is a restriction on the amount of plastic that can be recycled mechanically. For each of the case studies, nine epsilon values were used. This is obtained by discretizing between the best environmental objective value (when GWP is minimized) and the worst environmental objective value (when Profit is maximized), which ensures that the entire feasible space is considered. Also, to guarantee a strong Pareto, each individual optimization problem was solved to 2 % optimality. It should be noted that there is no other Pareto solution that dominates each of the Pareto solutions. Thus, each reported Pareto point is a strong Pareto optimal solution.

The results indicate that the Pareto curve for CON-MRL and ELE-MRL surpasses that of AVL-MRL. For every point on the frontier, we can achieve a better result (higher profit and lower GWP) for CON-MRL and ELE-MRL compared to AVL-MRL. Thus, if all the technologies are considered, better results can be achieved (increasing the feasible space). This increase in profit mainly due to the consideration of novel technologies based on process intensification in the design of the supply chain in CON-MRL and ELE-MRL cases. Despite their better performance, these technologies are still at Technology Readiness Levels (TRLs) of 5–7, and more investment is needed for a full-scale industrial implementation. In particular, it is important to maintain the heat and mass transfer characteristics at large scales since those are responsible for achieving yields of highly valuable products.

The three curves are also compared with the current mix of plastic waste management technologies in the US, see Fig. 6A). The current management mix is mostly composed of landfill and incineration. Landfill does not provide any valuable product and incineration is the

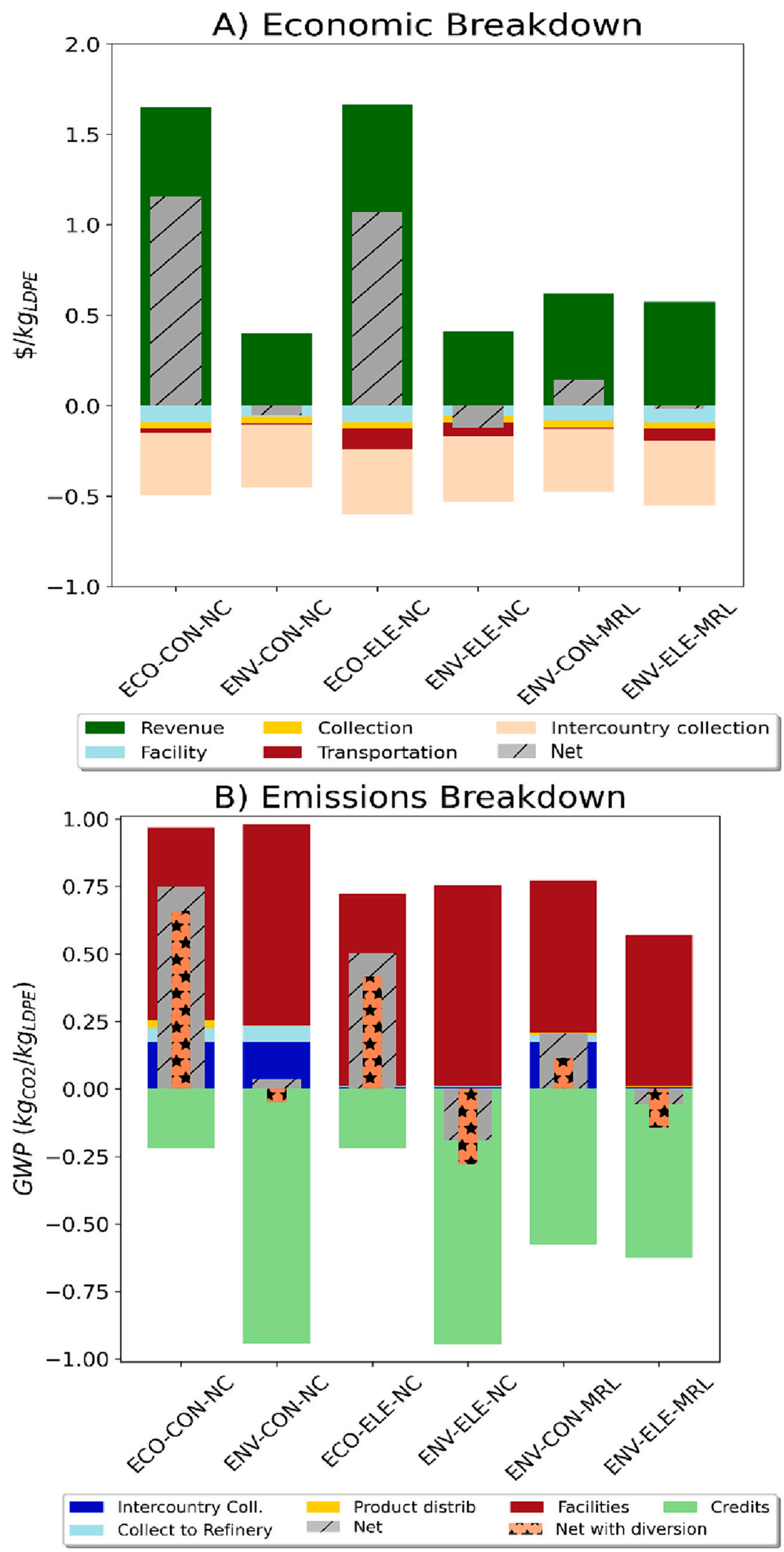

Fig. 3. Breakdown of A) economic contributors and B) emissions for each of the cases studied.

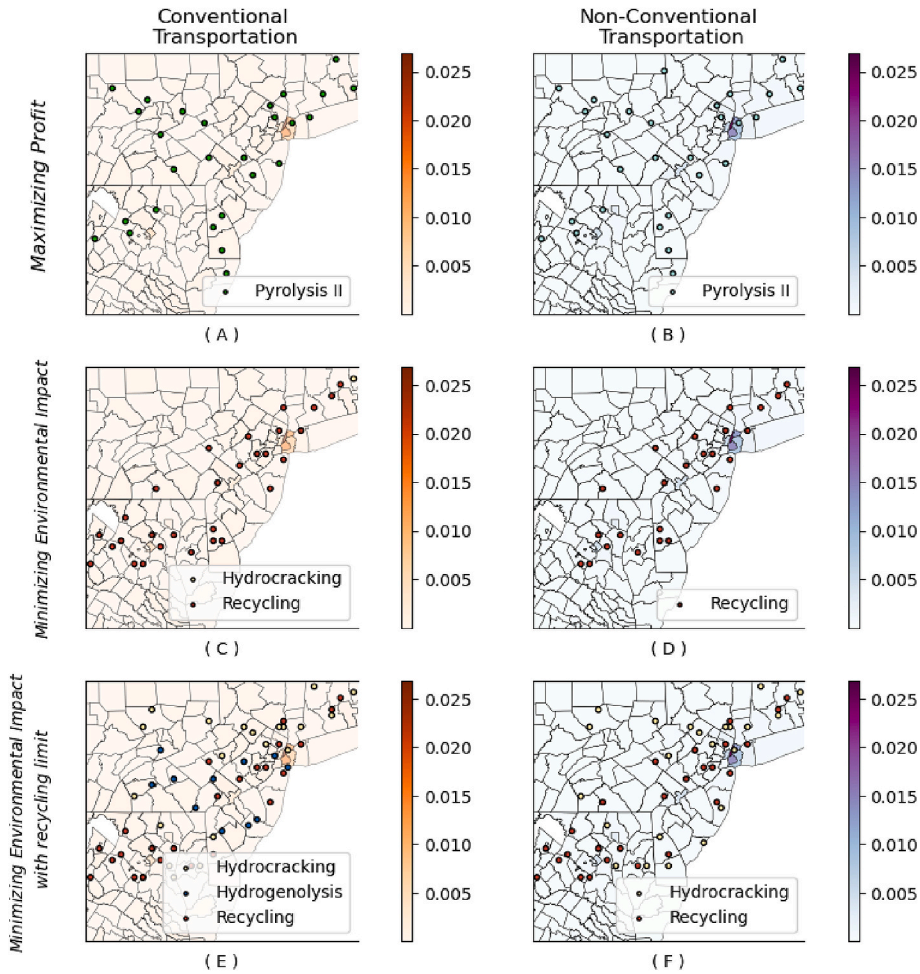

Fig. 4. Spatial distribution of technologies for the different scenarios. (a) ECO-CON-MRL; (b) ENV-CON-NC; (c) ENV-CON-MRL; (d) ECO-ELE-NC; (e) ENV-ELE-NC; (f) ENV-ELE-MRL. The bar scale represents the *population* density (*people*/*miles*^{2}) used for estimating the waste concentration.

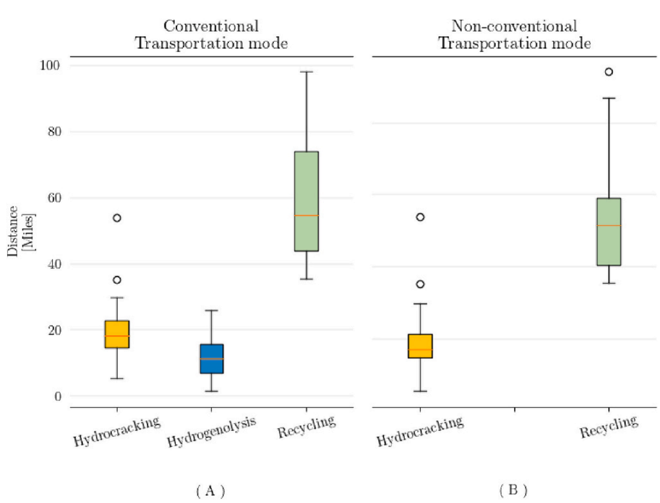

Fig. 5. Distribution of the distance between the technologies and the closest refinery for the technologies selected in the environmental optimization with limitations in the amount of plastic waste sent to mechanical recycling. The red line in the box plots represents the mean distance of the technology to the closest refinery, and the error bars represent the values with a confidence interval of 95% for the technology to be located in the refinery.

most emission intensive technology since it transforms all the carbon of LDPE into CO_2 emitted to the atmosphere. As a result, the emissions are higher than those obtained by three curves. It is important to note that the Pareto curves do not include the "Diversion" term of Eq. (7) to facilitate the comparison with business-as-usual plastic waste management. This term corresponds to the GWP of the point "Current Mix US". Thus, the discount of this term from the one of the plot determines the decarbonization potential of the Pareto curves according to a system expansion approach. Apart from the environmental comparison, the economic comparison shows that the value extracted from plastic waste in the US is almost null. This reflects the high contribution of landfills, 75 %, where no added value is generated.

Further details are provided on the technologies selected in each Pareto curve. The CON-MRL case identifies intermediate tradeoffs in technology selection; see Fig. 6, B). In the Pareto curve, multiple technologies coexist, and the choice depends on the point and the policies applied, environmental or economic focused. Among all technologies, Pyrolysis-2 is preferred to maximize profitability except when the primary guide is purely environmental. In such a case, mechanical recycling, hydrocracking, and hydrogenolysis are selected. Hydrocracking is also selected in all the intermediate points except for the pure economic objective, suggesting that a combination of mechanical recycling, hydrocracking, and pyrolysis is recommended on the Pareto frontier. This combination of multiple technologies is required for plastic waste management to be profitable and is neutral or negative in CO_2 emissions; see the feasible region with negative emissions in Fig. 6, A). Feasibility is achieved by combining technologies that decrease

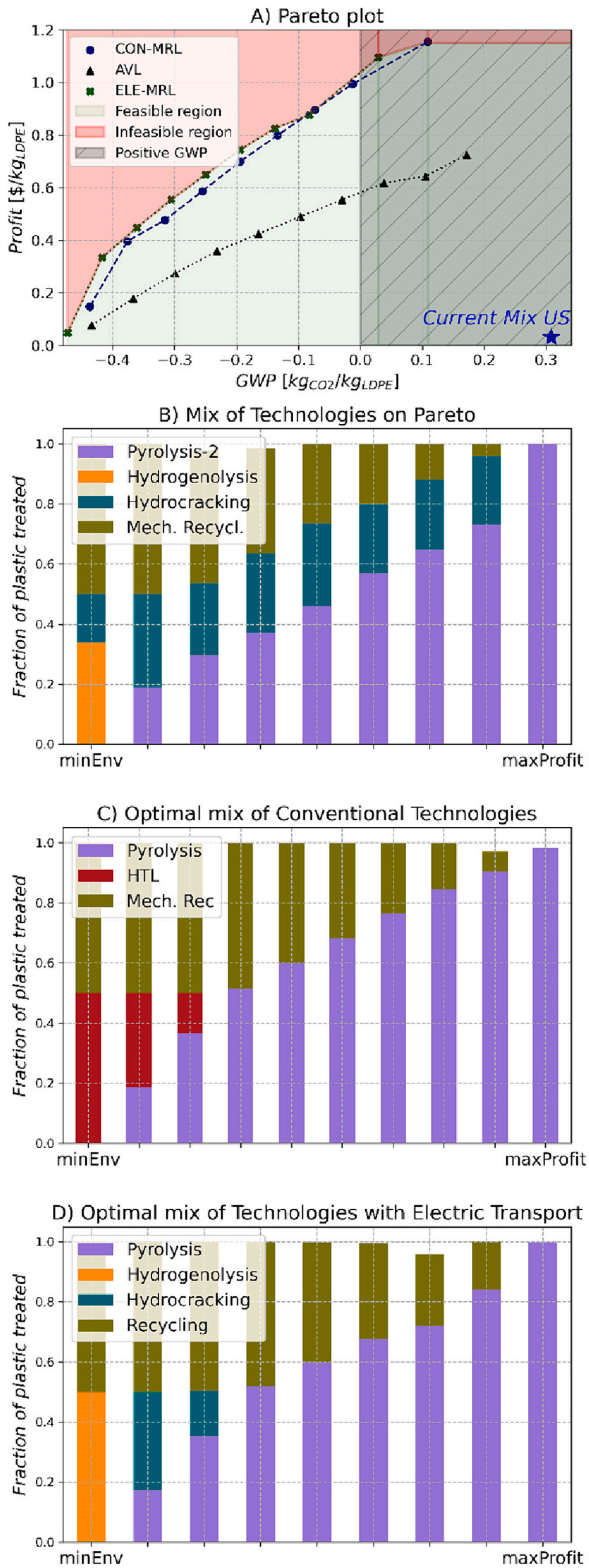

Fig. 6. Results from the Pareto case studies. A) Pareto fronts obtained for each case study without considering the "Diversion" term compared to the current mix of plastic waste management technologies in the U.S. B) Mix of all the possible technologies at each of the points of the Pareto front point when conventional transportation is used. C) Mix of conventional existing technologies in the Pareto front with conventional transportation. D) Mix of technologies when electric transportation.

emissions (such as mechanical recycling) that foster profitability (Pyrolysis). However, pyrolysis using microwave-based technology and hydrocracking are still under development on a large scale, so their implementation can take years of development.

Alternatively, the multi-objective analysis was carried out using solely existing industrial-scale technologies (AVL-MRL). In this case, the model selects a combination of mechanical recycling, Pyrolysis-1, and hydrothermal liquefaction. The profitability and the feasible region are smaller. The selection combines mechanical recycling and pyrolysis, with HTL as an intermediate technology; see Fig. 5(C). It is interesting to note that the desired combination in the environmental objective minimization only selects HTL and mechanical recycling. Although HTL generates fewer valuable products (a higher fraction of paraffin than olefins), it has a higher fraction of liquids and is lower in petrol gases, which emits less CO_2 in transportation. Thus, under environmental optimization in regions far from the refineries, HTL is preferred. It is significantly interesting that gasification, suggested by another work based on material flow analysis for Europe, is not selected (Lase et al., 2023). However, as we show in our previous detailed TEA and LCA analysis of the process, gasification from plastic waste is less economically competitive than gasification from other sources (e.g., natural gas biogas). The hydrogen: carbon ratio of sources like natural gas and biogas is higher than that of LDPE, making them more attractive due to the more efficient production of hydrogen.

The last case study corresponds to the Pareto front when electric trucks are used as an alternative (ELE-MRL); in comparison with conventional transportation, electric trucks promote the implementation of valuable technologies like pyrolysis for a wider range of the Pareto front, reducing the contribution of hydrogen catalytic technologies (e.g., hydrocracking). This suggests that implementing pyrolysis as an alternative to mechanical recycling can be preferred, and technologies like hydrocracking or hydrogenolysis can only appear in stages of decarbonization when minimization of GWP will be preferred against economics.

5. Conclusions

This work has presented a supply chain design study for the collection of waste plastics involving recycling and upcycling technologies on the East Coast of the United States. Our results show that the selection of the technology, capacity, and transportation mode is crucial for a sustainable supply chain. From all cases studied, the following conclusions can guide further development in plastic waste management in future works.

5.1. *Among technologies, pyrolysis is the most profitable option, and mechanical recycling minimizes the GWP*

Both technologies are necessary for the sustainable management of plastic waste. As pointed out in other published studies, pyrolysis and mechanical recycling will be dominant in the short term. Mechanical recycling is less emission-intensive, but it cannot recycle plastic waste infinitely, and microwave pyrolysis (electro-upcycling) generates profitable products like olefins. In this work, microwave pyrolysis (electro-upcycling) is preferred due to the higher fraction of olefins generated. However, the technology has a readiness level of 7, making it necessary to further work on treating higher amounts of plastic waste and reduce the cost of scale-up.

5.2. *Upcycling is essential and a threat*

Combining upcycling technologies and mechanical recycling is recommended in all the Pareto solutions to balance the economic and environmental objectives. Mechanical recycling and pyrolysis must coexist to ensure a profitable and CO_2 neutral waste management system. They can also be combined with novel catalytic technologies, like hydrocracking and hydrogenolysis, which are expected to make a smaller contribution. From an environmental point of view, it is suggested that thermochemical technologies be used to collect plastic waste from regions close to the refinery whereas in remote areas, plastic waste can be treated mechanically. Finding the right balance between both approaches, mechanical and chemical recycling, will require the development of regulatory policies.

5.3. Designing sustainable supply chains to minimize the GWP requires simultaneous consideration of transportation decarbonization

The introduction of electric transportation does not significantly modify the plant distribution from an economic point of view, but it affects the plant distribution when the GWP is minimized. Electrified transportation favors using larger plants (more centralized facilities) when the GWP is minimized. As a result, the emissions are governed by processes that require fewer processing alternatives. This result signifies that waste management cannot be carried out based on technologies alone and must simultaneously address other environmental problems, such as the electrification of transportation.

5.4. Collecting plastic waste locally is critical to the profitability and emissions of the entire plastic waste management supply

Among the different parts of a supply chain, the collection from houses to the collection facilities is determined to have the greatest environmental impact. Future works need to connect both scales (municipal with regional and national) and address specific conditions in the generation. It is important to consider the type of plastic and spatial distribution of the waste generated in residential complexes.

CRediT authorship contribution statement

Oluwadare Badejo: Writing – original draft, Methodology, Conceptualization. **Borja Hernández:** Writing – original draft, Methodology, Conceptualization. **Dionisios G. Vlachos:** Writing – review & editing, Project administration, Conceptualization. **Marianthi G. Ierapetritou:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.04.021.

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