TECHNO-ECONOMIC EVALUATION OF INFRASTRUCTURES FOR THERMOCHEMICAL UPCYCLING OF PLASTIC WASTE

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Abstract

Plastic pollution poses threats to the global ecosystem and human health. Existing recycling technologies have not affected significant plastic waste reductions, primarily due to poor economic performance and a limited number of recyclable plastic categories. New thermochemical technologies offer a means of upcycling plastic wastes; converting waste plastic into value-added chemicals. We use systems engineering modeling and market analysis to explore the economics, environmental impact, and potential supply chain structure of thermochemical plastic upcycling infrastructure to produce virgin plastic and fuel oil from post-consumer plastic waste. Our results reveal that the proposed infrastructures could generate more than $1 billion in annual profit in the Midwest region of the US, representing a significant incentive to install plastic upcycling infrastructure. Our results also reveal that producing virgin polymers from plastic waste results in half the emissions of waste incineration, in addition to reducing the need for petroleum-sourced virgin material. Market analysis reveals that post-consumer plastic waste has an inherent market value of $500/ton, demonstrating that waste becomes a valuable feedstock when attached to a profitable value chain.

Keywords

Plastic Upcycling, Techno-Economic Analysis, Supply Chain, Pricing.

Introduction

Plastic waste production in the United States increased 90-fold between 1960 and 2020(Agenda, 2016). As of 2016, it is estimated that per capita plastic waste production in the US is 130kg/year(Law et al., 2020). This rapid growth has outpaced the growth of recycling infrastructure. Most plastic is landfilled – some 55% of all plastic ever produced – and about 30% remains in use at present, leaving 6% of plastic that has been recycled(Ritchie and Roser, 2018). Landfilling leads to soil eutrophication, pollutes groundwater, and makes land revival nearly impossible. Present estimates suggest potential landfill sites meeting regulatory requirements will provide about 65 years of capacity(Rudolph et al., 2020). Existing plastic waste management techniques like incineration, release large amounts of carbon dioxide along with toxic gasses that are neurotoxic and carcinogenic(Verma et al., 2016). Plastic waste is now commonly cited as a global threat, owing to the lack of any scalable technology to mitigate it.

Existing plastic waste recycling infrastructures are primarily centered around polyethylene terephthalate (PET, plastic resin identification code 1) and high-density polyethylene (HDPE, 2). Postconsumer plastic waste collected through recycling programs is delivered to material recycling facilities (MRFs) that separate and (typically) sort waste into three streams: PET bottles, HDPE bottles, and everything else, including all plastics of types 3–7, and non-bottle PET and HDPE plastics. This third catch-all stream is generally unrecyclable within the US, comprises more than 80% of post-consumer plastic, and is ultimately landfilled(Smith, 2015). The PET and HDPE bottle streams are mechanically recyclable. These are delivered to a plastic reprocessing facility (PRF) where they are washed, ground, melted, and extruded to form new plastics. While mechanical recycling addresses only a small portion of plastic waste, there are well-established markets for recycled PET and HDPE bottles in the US. The primary limitation to mechanical recycling is that melting and regranulation degrade PET and HDPE over successive cycles, meaning recycled plastics are not suitable for certain applications, due to appearance or material quality losses.

Chemical recycling processes can overcome the limitations of mechanical recycling. Chemical recycling processes typically break down waste plastic streams into raw monomers, suitable to polymerization to create a virgin plastic from a waste stream. Owing to this, chemical recycling is often called upcycling, because the products obtained are chemically new. The upcycling approach, breaking down and repolymerizing plastics avoids the quality losses associated with mechanical recycling. In this paper, we examine the economic potential of thermochemical upcycling technologies, which have been the focus of intense research and re-

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cent interest(Sharuddin et al., 2016).

Thermochemical upcycling technologies comprise the majority of known upcycling methods, and have been the subject of intense research. Existing research exploring pyrolysis and steam cracking have primarily focused on reactor design(Al-Salem, 2019), process intensification(Onwudili et al., 2009), catalysts(Luo et al., 2000), and techno-economic analysis (Gracida-Alvarez et al., 2019). We aim to fill a gap within the literature, specifically, integrating TEA of plastic upcycling technologies with the design and operation of the associated infrastructure. In our study we consider infrastructure elements comprising plastic collection, sorting, cleaning, grinding, and chemical processing, including the transportation of raw materials, intermediates, and final products to consumers. With this approach, we explore the economic viability of plastic upcycling infrastructure, and determine optimal infrastructure design that maximizes profitability. In our view, designing profitable upcycling infrastructure is the best way to encourage the adoption of circular economic practices. We also are interested in the value of plastic waste as a resource, which has not (to our knowledge) been the focus of prior research. This value is a function of the products that can be recovered from waste plastic and the cost of processing it.

To explore these research questions we conduct a holistic analysis integrating TEA models of plastic upcycling technologies (see Figure 1) within an infrastructure optimization framework. The framework solves an optimization problem that determines technology selection, sizing, placement, and transportation logistics simultaneously. Our objective is to design thermochemical plastic upcycling infrastructure with maximum profitability, and to evaluate the economic potential and sustainability of this infrastructure. Figure 1 illustrates schematic representations of four plastic upcycling infrastructures, highlighting the products and technologies involved in each. We compare these different infrastructures in terms of economic viability and environmental impact. This analysis provides insights into upcycling policy and the design of plastic upcycling infrastructures. Moreover, we will be able to estimate the value of plastic waste and how it could support new recycling systems within the US.

Model Formulation

Our infrastructure designs in this work are evaluated in their ability to serve the upper Midwest region of the US comprising Wisconsin, Illinois, Minnesota, and Iowa. In Figure 2, we treat each county as a geographical node and use $\mathcal{N}$ to represent 360 counties of the studied region. We consider each county as a plastic supplier and use $\mathcal{S}$ to denote 360 plastic suppliers in the studied region. Each plastic supplier $i \in \mathcal{S}$ has a plastic supply flow $s_i \in \mathbb{R}_+$, maximum supplying capacity $\bar{s}_i \in \mathbb{R}_+$, location $n(i) \in \mathcal{N}$ and plastic supplying price $\alpha_i^s \in \mathbb{R}_+$. In this work, the plastic supplying price is assumed to be zero. For infrastructure I,III and IV, the plastic is provided in the form of mixed recyclable materials. For infrastructure II, since plastic is sorted by people in their households, suppliers provide sorted plastic directly.

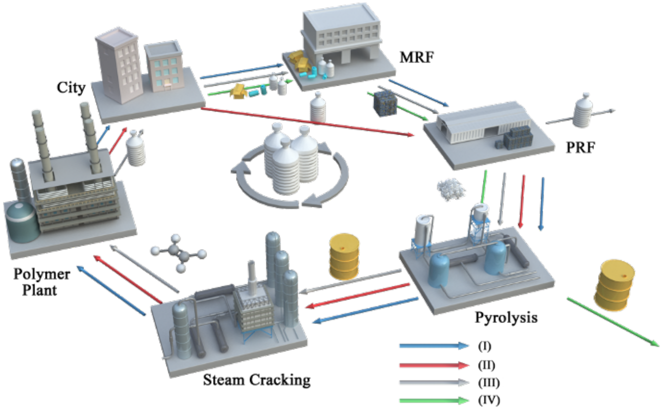

Figure 1: **Schematic of the proposed plastic wastes upcycling infrastructures.** We explore four infrastructure designs, each comprising some combination of five technologies. These include: MRFs that collect recyclable materials from consumers and sort out plastic. Plastic waste is baled and shipped to PRFs where it is washed and ground into flake. The plastic flake is then converted into pyrolysis oil, olefins and virgin polymers using thermochemical technologies, including pyrolysis, steam cracking, and polymer synthesis. Detailed descriptions of each technology are available at : `https://chemrxiv.org/engage/chemrxiv/article-details/6349a490de2a213e57a5771d`. The four plastic upcycling infrastructures are (I): A status quo case in which plastic is collected, washed, and sorted following existing US practices, then upcycled through pyrolysis and steam cracking to produce virgin monomers and finally polymers for sale to consumers. In case (II) we explore the impact of consumers separating plastic in their homes, precluding the need for the MRF in the infrastructure. The case is otherwise identical to (I). In case (III) we examine plastic upcycling infrastructure designed to separate PET and HDPE bottles for mechanical recycling, with remaining plastics upcycled as in (I). Finally, in case (IV) plastics are converted to pyrolysis oil for shipment to the Gulf region for additional processing. Case (IV) ends with the pyrolysis oil, with no plastic upcycling in the Midwest region.

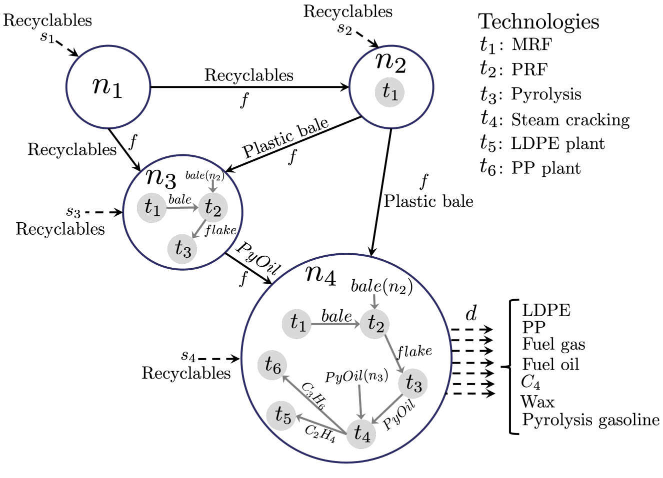

Figure 2: **Schematic of supply chain network**

We use $\mathcal{P}$ to denote the set of products (including raw materials, intermediate and final products). For infrastructure I, the product set is defined as $\mathcal{P} :=$ {recyclables, plastic bale, plastic flake, pyrolysis oil, ethylene, propylene, C_4, pyrolysis gasoline, fuel gas, fuel oil, LDPE, PP, wax}. For infrastructure II, since the MRF is bypassed, the product set is defined as $\mathcal{P} := \{$plastic waste, plastic flake, pyrolysis oil, ethylene, propylene, C_4, pyrolysis gasoline, fuel gas, fuel oil, LDPE, PP, wax$\}$. For infrastructure III, PET and HDPE bottles are mechanically recycled. Therefore, the product set is defined as $\mathcal{P} := \{$recyclables, #1 plastic bale, #2 plastic bale, mixed plastic bale, mixed plastic flake, PET flake, HDPE flake, pyrolysis oil, ethylene, propylene, C_4, pyrolysis gasoline, fuel gas, fuel oil, LDPE, PP, wax$\}$. For infrastructure IV, pyrolysis is the only thermochemical facility. Therefore, the product set is defined as $\mathcal{P} := \{$recyclables, plastic bale, plastic flake, pyrolysis oil$\}$.

$$\max_{(s,d,f,\xi,y)} \sum_{j\in\mathcal{D}} \alpha^d_j d_j - \sum_{i\in\mathcal{S}} \alpha^s_i s_i - \sum_{\ell\in\mathcal{L}} \alpha^f_\ell f_\ell - \sum_{t\in\mathcal{T}} \alpha^\xi_t \xi_t - \sum_{t\in\mathcal{T}} \alpha^y_t y_t \tag{1a}$$

$$\text{s.t.} \sum_{i\in\mathcal{S}_{n,p}} s_i - \sum_{j\in\mathcal{D}_{n,p}} d_j + \sum_{\ell\in\mathcal{L}^{in}_{n,p}} f_\ell - \sum_{\ell\in\mathcal{L}^{out}_{n,p}} f_\ell$$

$$+ \sum_{t\in\mathcal{T}_n} \gamma_{t,p}\, \xi_t = 0,\ (n,p) \in \mathcal{N}\times\mathcal{P} \tag{1b}$$

$$s_i = \bar{s}_i,\ i \in \mathcal{S} \tag{1c}$$

$$\xi_t \le y_t \bar{\xi}_t,\ t \in \mathcal{T}. \tag{1d}$$

We have the set of consumers $\mathcal{D}$ bidding for final products (LDPE, PP, fuel gas, fuel oil, C_4, wax, pyrolysis gasoline). For each final product at each node, there is a corresponding consumer $j \in \mathcal{D}$. Each consumer has a demand flow $d_j \in \mathbb{R}_+$, requested product type $p(j) \in \mathcal{P}$, location of consumer $n(j) \in \mathcal{N}$, and product purchasing price $\alpha^d_j \in \mathbb{R}_+$. The product purchasing prices equal to the market values of these products.

Technologies are indexed $t \in \mathcal{T}$. We denote the subset of technologies located in node n as $\mathcal{T}_n \subseteq \mathcal{T}$, with $\mathcal{T}_n := \{t \in \mathcal{T} \mid n(t) = n\}$. Each county is considered a potential location for the technologies. Therefore, the proposed plastic upcycling infrastructure comprises 360 potential sites for installing technology facilities.

For infrastructure I and III, we have in total six technologies considered: MRF, PRF, pyrolysis, steam cracking, LDPE plant and PP plant. For infrastructure II, since MRF is bypassed, we have five technologies involved: PRF, pyrolysis, steam cracking, LDPE plant and PP plant. For infrastructure IV, there are only three technologies, including MRF, PRF and pyrolysis. Each technology is affiliated with yield factors $\gamma_{t,p} \in \mathbb{R}$, location $n(t) \in \mathcal{N}$, reference product $p(t) \in \mathcal{P}$, processing capacity $\bar{\xi}_t \in \mathbb{R}_+$, operating cost $\alpha^\xi_t \in \mathbb{R}_+$, number of facilities installed $y_t \in \mathbb{Z}_+$, annualized installation cost $\alpha^y_t \in \mathbb{R}_+$. Yield factors $\gamma_{t,p} \in \mathbb{R}$ denote the units of product p consumed/generated per unit of reference product $p(t)$ consumed/generated in the technology t (e.g., how many units of pyrolysis oil can be produced from one unit of plastic flake using pyrolysis). Here, $\xi_t \in \mathbb{R}_+$ is the amount of product $p(t)$ processed at technology t.

Transport providers are indexed as $\ell \in \mathcal{L}$ with flow $f_\ell \in \mathbb{R}_+$, cost $\alpha^f_\ell \in \mathbb{R}_+$, product type transported $p(\ell) \in \mathcal{P}$, sending (origin) node $n_s(\ell) \in \mathcal{N}$ and receiving (destination) node $n_r(\ell) \in \mathcal{N}$. To avoid transporting olefins, polymer plants are built with steam cracking facilities in the same location. Transportation providers only move recyclables (plastic waste in infrastructure II), plastic bale, plastic flake and pyrolysis oil cross nodes. These four products could be shipped cross any pair of nodes in the supply chain network. To simplify the notation for transport, We define $\mathcal{L}^{in}_{n,p}$ as a subset of transport provider $l \in \mathcal{L}$ who sent product p to node n. Subset $\mathcal{L}^{out}_{n,p}$ includes transport provider who transport p away from n.

The objective function is maximizing the annual profit of plastic upcycling infrastructure as eq.(1a). It is defined as demand revenues minus supply, technology, and transportation costs. Eq.(1b) ensures that each product $p \in \mathcal{P}$ at each node $n \in \mathcal{N}$ is in balance. Constraint (1c) ensures that all the plastic wastes are provided for upcycling. Constraint (1d) imposes capacity bounds for each technology; the processing capacity of technology is zero if the facility is not built ($y_t = 0$), otherwise ($y_t > 0$), the total capacity is given by the per facility capacity ($\bar{\xi}_t$) and the number of facilities built (y_t). This optimization model is a mixed-integer linear programming (MILP).

After solving the above MILP, we fix the integer variable y_t. We transform the above MILP into a linear programming (LP). This transformation is equivalent to having technologies installed. The goal is to optimize the plastic upcycling infrastructure with predefined number, size and location of facilities.

$$\max_{(s,d,f,\xi)} \sum_{j\in\mathcal{D}} \alpha^d_j d_j - \sum_{i\in\mathcal{S}} \alpha^s_i s_i - \sum_{\ell\in\mathcal{L}} \alpha^f_\ell f_\ell - \sum_{t\in\mathcal{T}} \alpha^\xi_t \xi_t \tag{2a}$$

$$\text{s.t.} \sum_{i\in\mathcal{S}_{n,p}} s_i - \sum_{j\in\mathcal{D}_{n,p}} d_j + \sum_{\ell\in\mathcal{L}^{in}_{n,p}} f_\ell - \sum_{\ell\in\mathcal{L}^{out}_{n,p}} f_\ell$$

$$+ \sum_{t\in\mathcal{T}_n} \gamma_{t,p}\, \xi_t = 0, (n,p) \in \mathcal{N}\times\mathcal{P}, (\pi_{n,p}); \tag{2b}$$

$$s_i = \bar{s}_i,\ i \in \mathcal{S} \tag{2c}$$

$$\xi_t \le y_t \bar{\xi}_t,\ t \in \mathcal{T}. \tag{2d}$$

After solving the above problem, the dual variable $\pi_{n,p}$ of product balance constraints (2b) is derived. This variable sets values for the products at different geographical locations and acts as the market clearing prices. The plastic waste clearing price is then obtained. We implement above optimization models in the algebraic modeling package JuMP and solve all problems using Gurobi. The code is executed on a computing server that contains a 32 cores Xeon(R) CPU E5-2698 v3 @ 2.30GHz. The optimality gaps for both MILP and LP models are set as 0.01%.

Facility Location Analysis

Figure.3 I, II, III, and IV show the resulting infrastructure designs for each of the four cases. In cases I, II, and III (the solutions here are nearly identical) MRF locations follow population densities, with a large cluster of the units in the East to serve dense urban populations and a few units of various capacities located in less populated Northwest to serve consumers in wider areas. There are fewer PRFs, with

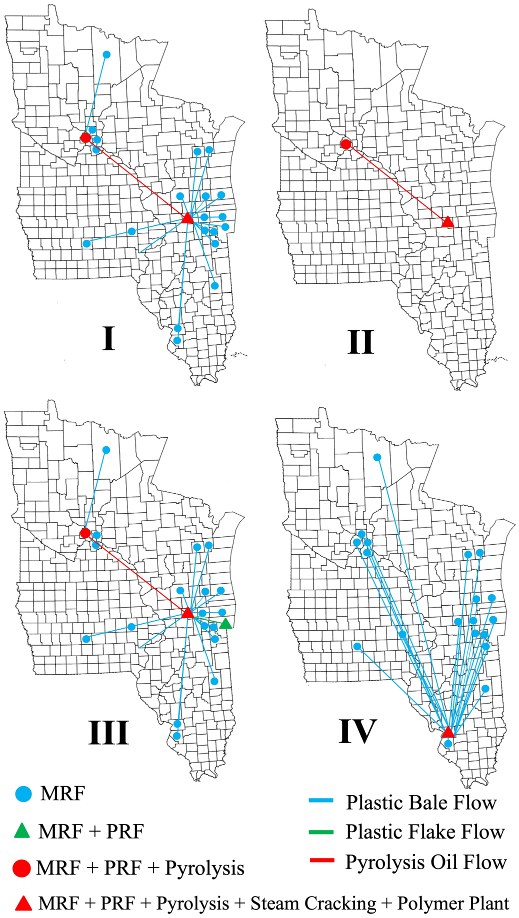

Figure 3: **Cost-effective design of plastic upcycling infrastructures**

one large unit serving the populous East and a smaller unit serving the Northwest. Pyrolysis units are located at the same sites as the PRFs, with the same number of units. A single steam cracking unit and polymerization facility are located in the East at the pyrolysis site, serving the entire area. In case IV, the MRF distribution is similar, but there is one large PRF and pyrolysis facility to produce pyrolysis oil. The difference in case IV is driven by transportation costs associated with sending pyrolysis oil to the Texas gulf coast.

An important distinction in our results is that our infrastructure design includes around 20 new MRFs. Existing MRFs in the Midwest are designed only to accept and process #1 and #2 plastic bottles; the MRFs in our design will be able to process mixed plastics. The MRF distribution follows from the economics of plastic waste: each tonne of recyclables shipped to an MRF yields only 0.23 tonnes of plastic waste. It is possible to have centralized PRFs because the plastic bales are more economical to transport. Centralization of the upcycling technologies (pyrolysis, steam cracking, and polymerization) is driven by high investment costs. In general, we observe distributed MRFs and centralized PRFs (and subsequent upcycling technologies) that capitalize on economies of scale. Specifically, our models suggest that centralized PRFs and thermochemical facilities should be installed in Hennepin County, Minnesota, and Winnebago County, Illinois (cases I, II, and III) and in case IV, that a single centralized facility be built in Madison County, southern Illinois.

Economic Viability

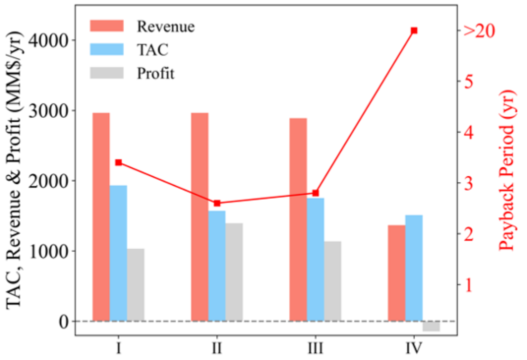

Figure 4: **TAC, revenue, annual profit, and the payback period (red line) of four infrastructures.** All the first three infrastructures generate up to 1 billion USD of profit and infrastructure II is the most profitable. The payback periods of these three infrastructures are less than four years. For infrastructure IV, the revenue cannot offset the TAC.

Figure 4 groups the revenues and TACs from the four cases and shows the resulting profits. Cases I, II, and III are all viable, with case II demonstrating that removing MRFs from the supply chain represents the largest increase in profits over the base case (I). Case III is more profitable than case I, and is able to take advantages of reductions in technology scale to decrease TAC while still producing value-added products. The hybrid mechanical-thermochemical route illustrates how thermochemical upcycling can work with existing recycling infrastructure to create value. Case IV has a negative profit, suggesting that pyrolysis oil alone is not a good solution for plastic waste management in the Midwest.

The large profit values observed in our cases suggest that incentive programs could be set up to reward consumers who wash and sort plastic in their homes. By creating incentive programs, consumers are reimbursed for providing a service, encouraging their participation in plastic waste management, and some of the most costly elements of the collection and separation are avoided. In this future scenario, consumers might have an alternative to local recycling collection programs in which clean, sorted plastics are picked up separately, weighed, and reimbursed. In short, by passing value on to consumers, we believe that recycling systems in the US can surpass the standards achieved in other countries.

Environmental Sustainability

The environmental sustainability is evaluated by quantifying the greenhouse gas emissions (GHGs) of the four plastic upcycling infrastructures using LCA methods (see supplementary information). GHG is commonly used as a metric for the sustainability of recycling systems; while other LCA metrics merit investigation, GHGs has unique industrial relevance. Our infrastructure designs produce different end products, which makes comparing sustainability in terms of final

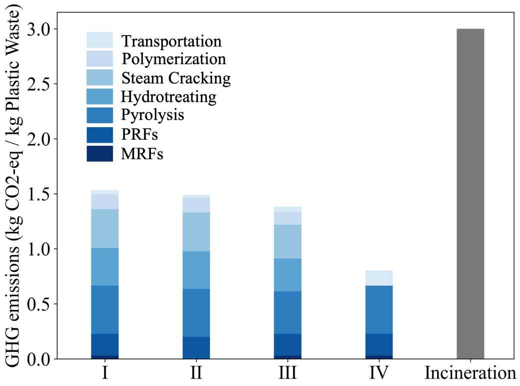

Figure 5: **Comparison and breakdowns of GWP of four plastics upcycling infrastructures.** The carbon emissions of these infrastructures are 50% lower than that of incineration.

products difficult. Instead, we choose plastic waste as the basis for GHGs calculations, since it is the raw material in all four design cases. Figure 5 presents a breakdown of resulting from the processing of 1 kg of plastic waste through each of the four infrastructure designs, plus a disposal case representing the GHGs associated with disposing of plastic waste by incineration.

As a baseline comparison, all four of our case studies outperform incineration as a means of plastic disposal. Breaking down the case study results, we find that the energy-intensive thermochemical processes (pyrolysis, hydrotreating, steam cracking, and polymerization) contribute about 80% of the GHGs, with the pyrolysis process contributing near a third of the total GHGs. Any improvements to these technologies will improve our proposed infrastructure. Focusing on case III, we observe that the diversion of the 12% of PET and LDPE bottles in plastic bales into mechanical recycling lowers the total energy requirement (and GHGs) per unit weight processed.. Although case IV has the lowest GHGs among the proposed upcycling infrastructures, it achieves a limited degree of circularity since the pyrolysis oil is the only final product. Apart from case IV, our most sustainable result has an impact estimated at 1.38 kg CO2 eq/kg plastic waste. Note that after accounting the avoided utility emissions of combusting plastic (emission savings associated with the avoided emissions of burning conventional fossil fuels for utilities), the GHGs of plastic incineration is 1.38 kg CO2 eq/kg of plastic waste, which is closed to the GHGs of case III. However, the GHGs of the proposed upcycling infrastructures could be less than 1kg CO2 eq/kg of plastic waste if the avoided emissions of producing polymers from fossil fuels are accounted.

These results have two important implications. First, thermochemical upcycling can reduce plastic waste accumulation by converting a substantial fraction of waste plastic into value-added new products. Second, thermochemical upcycling reduces the need for virgin plastics, demonstrating increased circularization of the plastic supply chain and greater sustainability in terms of GHGs. Creating a circular economy for plastics reduces US dependence on fossil fuels and natural gas.

Value of Plastic Waste

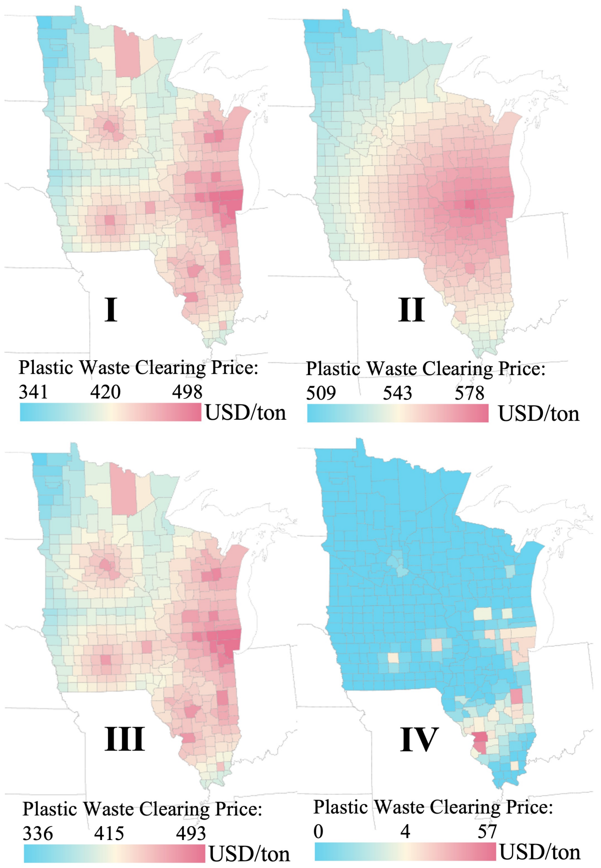

Figure 6: **Clearing price of plastic wastes in the Upper Midwest region.** Note that in case II we observe large positive values of plastic waste that create incentives for consumers to participate in the system.

The clearing price (also called locational marginal price, or LMP) of plastic waste in each county is illustrated in Figure 6. This clearing price reflects the value of plastic waste accounting for patterns of complex geographical distribution and the physical limits of logistic and processing technologies in the proposed plastic upcycling infrastructure. LMPs are obtained from our mathematical models, which are built at a county-level of resolution, providing county-level prices. The plastic waste clearing prices of infrastructure I range from 341-498 USD/ton. The clearing prices of plastic wastes are affected by their proximity to recycling facilities. The populated areas where MRFs are installed (e.g., Chicago, Milwaukee, Minneapolis, etc.) tend to have high clearing prices. Counties that are farther from service locations (e.g., western Minnesota) tend to have the lower clearing prices.

Transporting plastic waste to processing facilities incurs a distance-based cost, reducing the price of plastic waste the farther it is from a processing center. Although there are 22 MRFs installed in the studied region, the Chicago areas (e.g., Cook County, Lake County, McHenry County, Kane County, Lake County, Winnebago County) have the highest clearing price of plastic wastes (480-498 USD/ton). With the pyrolysis facilities located in Winnebago County, IL, very little transport is required to collect plastic bale nearby. With this geographical advantage consumers in the Chicago area enjoy high clearing prices.

Since infrastructure II has centralized PRFs and thermochemical facilities, the distribution of plastic waste clearing prices is apparent. The closer to Winnebago county Illinois, the higher the plastic clearing price. The clearing price of Winnebago county is up to 578 USD/ton. Note that the lowest clearing price of infrastructure II is 509 USD/ton (Kittson County in northwest Minnesota). Even the lowest clearing price of infrastructure II is still higher than the highest clearing price of infrastructure I. Bypassing MRFs means the costs are saved, and are reflected in the clearing price. These prices suggest that greater incentives could be made to encourage consumers to participate in the program. This consumer sorting behavior increases the average value of plastic wastes in the studied region by 123USD/ton (from 420 USD/ton to 543 USD/ton). The clearing prices of infrastructure III are almost identical to that of case I. Since the economy of infrastructure IV is the worst among the four infrastructures, most of the places have a clearing price of zero, confirming our intuition that Madison County, where PRF and pyrolysis facilities are installed, has the highest clearing price.

In summary, the most important observation concerning these clearing prices is that the plastic waste clearing prices are positive. This implies that plastic waste is a valuable commodity from which value-added products can be produced. Moreover, it suggests that the present paradigm in which US consumers pay for waste collection undervalues this commodity and does not create incentives that encourage meaningful participation in recycling infrastructure. Instead, our results suggest that there is sufficient value in plastic waste to pay consumers for plastic waste, opening up the possibility of new recycling incentives that improve sustainability and participation.

Conclusions

Driven by the global plastic crisis, the need for an economically viable and sustainable plastic upcycling infrastructure is unprecedentedly urgent. Leveraging a group of well-established chemical technologies, we proposed a set of plastic upcycling infrastructures that help mitigate plastic pollution. Results show that the disposal of plastic waste can be a profitable business. Our proposed designs I, II, and III are all economically viable options that create value. Moreover, these upcycling infrastructures mitigate the environmental pollution associated with landfilling and incineration. Furthermore, it alleviates dependence on crude oil and natural gas to make polymers and chemicals.

Our infrastructure designs assume various levels of public engagement. Case I is the status quo; consumers place mixed waste for collection, while in case II, consumers sort waste for pickup, alleviating the need for MRFs. We observed that this frees up value in the supply chain, but what we cannot determine is whether the value available will create the incentives needed to drive mass public participation in this type of program. If implemented, we aspire to a system similar to those in Europe7, with socially conscious plastic management incentivized through economic means. Additional research is needed to determine whether this type of arrangement is feasible within the economic constraints we have identified.

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