Sustainability assessment and pathways for U.S. domestic paper recycling

Enze Jin[1,*], Stijn van Ewijk[2,3], Koichi S. Kanaoka[3], Yohannes A. Alamerew[1], Hui Lin[4], Zhi Cao[5,6,7] Banafsheh Jabarivelisdeh[1], Kornel F. Ehmann[8], Marian R. Chertow[3], Eric Masanet[1,6]

[1] Bren School of Environmental Science and Management, University of California Santa Barbara, Santa Barbara, CA, USA

[2] Department of Civil, Environmental & Geomatic Engineering, University College London, UK

[3] School of the Environment, Yale University, New Haven, CT, USA

[4] Department of Electrical and Computer Engineering, Northwestern University, Evanston, IL, USA

[5] Energy and Materials in Infrastructure and Buildings, University of Antwerp, Antwerp, Belgium

[6] McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL, USA

[7] College of Environmental Science and Engineering, Nankai University, Tianjin, China

[8] Department of Mechanical Engineering, Northwestern University, Evanston, IL, USA

*Corresponding author (email: ejin@ucsb.edu)

Keywords: material recovery facilities, paper recycling, deinking process technologies, unit process modeling, techno-economic analysis

Abstract:

Dramatic changes in global recovered paper markets, triggered in large part by Chinese import restrictions, challenge the U.S. to find sustainable pathways for increasing the domestic paper recycling rate. This study presents a technology-rich process model of the U.S. domestic paper recycling industry to assess the energy consumption, carbon emissions, and system costs. A scenario analysis shows the viability of three potential pathways for achieving the national goals of a 15% increase in both the paper recycling rate and the recycled paper utilization rate. The results suggest that the national goals can be achieved by recovering 80% of recyclable papers from households and commercial stores, while trading all exported bales to domestic recovery with additional investments in processing capacity expansion. The deployment of advanced technology can enable material recovery facilities (MRFs) and paper mills to produce most recycled paper products that are more energy efficient with fewer CO_2 emissions.

1. Introduction

Paper is one of the most widely recycled materials in the U.S., with the domestic paper recycling rate in recent years between 66% and 68% (American Forest & Paper Association, 2021).

Replacing primary feedstocks with recovered paper can result in substantial resource and CO_2 emissions savings. The U.S. Environmental Protection Agency (EPA) reported that 46 million tonnes of paper and paperboard were recycled in 2018, avoiding over 155 million tonnes of CO_2 emissions (U.S. EPA, 2020a). Of these, more than 21 million tonnes of recovered paper were exported to other countries, among which China is the largest receiving country (ISRI, 2020). Exporting recyclable papers as a waste management practice creates win-win situations in terms of profitability for both importer and exporter countries (Li et al., 2022). The domestic paper recycling only accepts recyclable papers with best quality that meet the standards of complex deinking processes. Only 20% of recyclable paper were reprocessed domestically into recycled paper products due to the limited availability of good quality sorted paper and low market demand for recycled paper products (U.S. GAO, 2020). Lower quality sorted papers were exported to China for recycling or ended up in incineration and landfill. However, U.S. recyclers have endured severe impacts from China's scrap material import ban: U.S. exports of paper and paperboard commodities to China in 2018 were 30% less than in 2017 (ISRI, 2020). When the Chinese government implemented a complete ban on foreign waste in 2021, the export of recovered paper from the U.S. fell from 6.4 million tonnes in 2018 to 0.5 million tonnes in 2021 (Li et al., 2022). Other nations have adopted their own policies restricting or banning waste imports, effectively shuttering key alternative markets for U.S. scrap exports. To address the challenges of scrap export, the U.S. government and the paper industry need a long-term strategy for increasing domestic recycling because there are fewer sinks for the recyclable materials.

Another reason for a concerted strategy is the national goals for recycling. The REMADE Institute – a federal institute co-funded by the U.S. Department of Energy - was established to enable advanced technology innovations that could reduce embodied energy and carbon emissions for recovery, remanufacturing, and reuse processes. The REMADE Institute aims to achieve the national goal of a 15% increase in the U.S. paper and paperboard recycling rate (RR) and utilization rate (also defined as recycled input rate (RIR)), as well as increasing the energy efficiency by 25% and lowering carbon emissions by 20% for the pulp and paper industry (REMADE Institute, 2022). While it is clear that China's scrap ban has incited domestic development of fiber mills and markets, considerable focus is being placed on process technology innovations to improve both U.S. paper recycling rates and recycled paper quality. However, it remains elusive how and to what extent changes in process technologies and operating practices could help improve the economic and environmental performance of the U.S. paper recycling system compatible with the national goals.

The literature has evaluated the economic and environmental performance of the U.S. paper recycling system through material flow analysis (MFA) and life cycle assessment (LCA). Most paper-related MFA studies (Krones, 2016; Sevigné-Itoiz et al., 2015; van Ewijk et al., 2018) provide macroscopic results of the paper and pulp system, but are unable to evaluate how process parameters and technology improvements would affect the economic and environmental performance of the U.S. paper recycling system. LCA studies of pulp and paper production systems (Heath et al., 2010; Leon et al., 2015; Man et al., 2019; Ozalp and Hyman, 2006; Silva et al., 2015; Tomberlin et al., 2020) provide benchmarks of energy and carbon intensities for industry, but cannot capture the impacts of various system parameters, such as the recyclable paper quantity and contamination rate, availability of advanced technologies, and trade. Moreover, decisionmakers in industry and government need to know the tradeoffs between environmental benefits and economic costs. Currently, no systems analysis tools are available that capture the carbon and economic performance of U.S. paper recycling.

This study developed a technology-rich process model, the Paper Recycling Integrated System Model (PRISM), to 1) assess the system-level environmental and economic performance, and 2) identify the actions that may be taken to achieve the goals for the U.S. paper recycling industry. The PRISM can assess how changes in system parameters – including expansion of collection and sorting systems, investments in processing capacity and technologies, changes in scrap quantities and qualities, and regulatory, logistical, and trade developments – can affect the profitability and environmental benefits of the domestic fiber recycling industry. PRISM represents current and emerging technologies in recovered paper sorting and reprocessing through a set of technical parameters related to energy efficiency, carbon intensity, and economic cost. It allows users to explore how technological innovations can enable the U.S. paper recycling industry to increase recycling rates, improve its profitability, and maximize its environmental benefits under different economic, market, and regulatory conditions.

By conducting a scenario analysis, this study aims to answer the following questions of interest for industrial stakeholders and policymakers: 1) what actions may be taken to achieve the goal of increasing the domestic paper recycling rate, 2) what are the investment costs for the domestic paper recycling industry to achieve national goals, 3) what are the improvements in energy consumption and GHG emissions for the deployment of advanced recycling process technologies at MRFs and recycling paper mills, and 4) what is the role of trade in achieving the goal of increasing the recycled paper utilization rate? The next section introduces the modelling framework, unit process approach, data sources, and scenario design. Section 3 presents the baseline system performance, and the environmental and economic performance at the national and facility levels for all scenarios. Section 4 discusses the findings for the domestic paper recycling industry and the strategic insights for achieving the national goals. Finally, Section 5 presents the conclusions.

2. Material and Methods

2.1 Modeling framework

The PRISM is a bottom-up technology assessment model that tracks material flows, energy use, and greenhouse gas (GHG) emissions occurring in the life cycle stages from cradle to gate, including recyclable paper generation, collection, recovery at material recovery facilities (MRFs), and reprocessing at recycling paper mills. The model focuses on the life cycle of recycled paper only and not the life cycle of virgin paper products. In addition, the scope of the model excludes the forest carbon storage that saved from recycled products. The purpose of the model is to analyze pathways for increased paper recycling rate and recycled paper utilization rate to indicate how paper recycling industry can reduce raw material use for pulp and paper production, and further reduce the energy consumption and GHG emissions of paper production based on the REMADE national goals. The model cannot be used to estimate the potential benefits of recycling in terms of the avoided emissions through a reduction in wood extraction and processing. In addition, the PRISM does not aim to forecast the future supply and market of domestic paper recycling system based on a time series fashion. This study mainly investigates the effects of dynamic changes in collection behaviors and advanced technology adoption of sorting and reprocessing stages on the national paper recycling goals. For illustrative purposes, the results section includes a comparison of modeled recycled paper emissions with literature values for virgin paper production.

Figure 1 depicts the modeling framework including separate descriptions of the model for recovery at MRFs and reprocessing at recycling paper mills. The configuration shown in Figure 1 represents typical operations in the U.S., but the setup of unit processes may differ slightly across MRFs and recycling paper mills. The model differentiates between four recyclable post-consumer fibers by grade (old corrugated cardboard (OCC), old newspapers and magazines, office papers, and mixed papers) and five final paper products by grade (newsprint, market deinked pulp, tissue, containerboard, and other paperboards) It tracks the quality implications of processing a specific fiber grade into a specific final product grade. The typical configurations of paper recovery at a recycling paper mill for each final paper grade are depicted in Figure S1 in the Supplementary Information (SI).

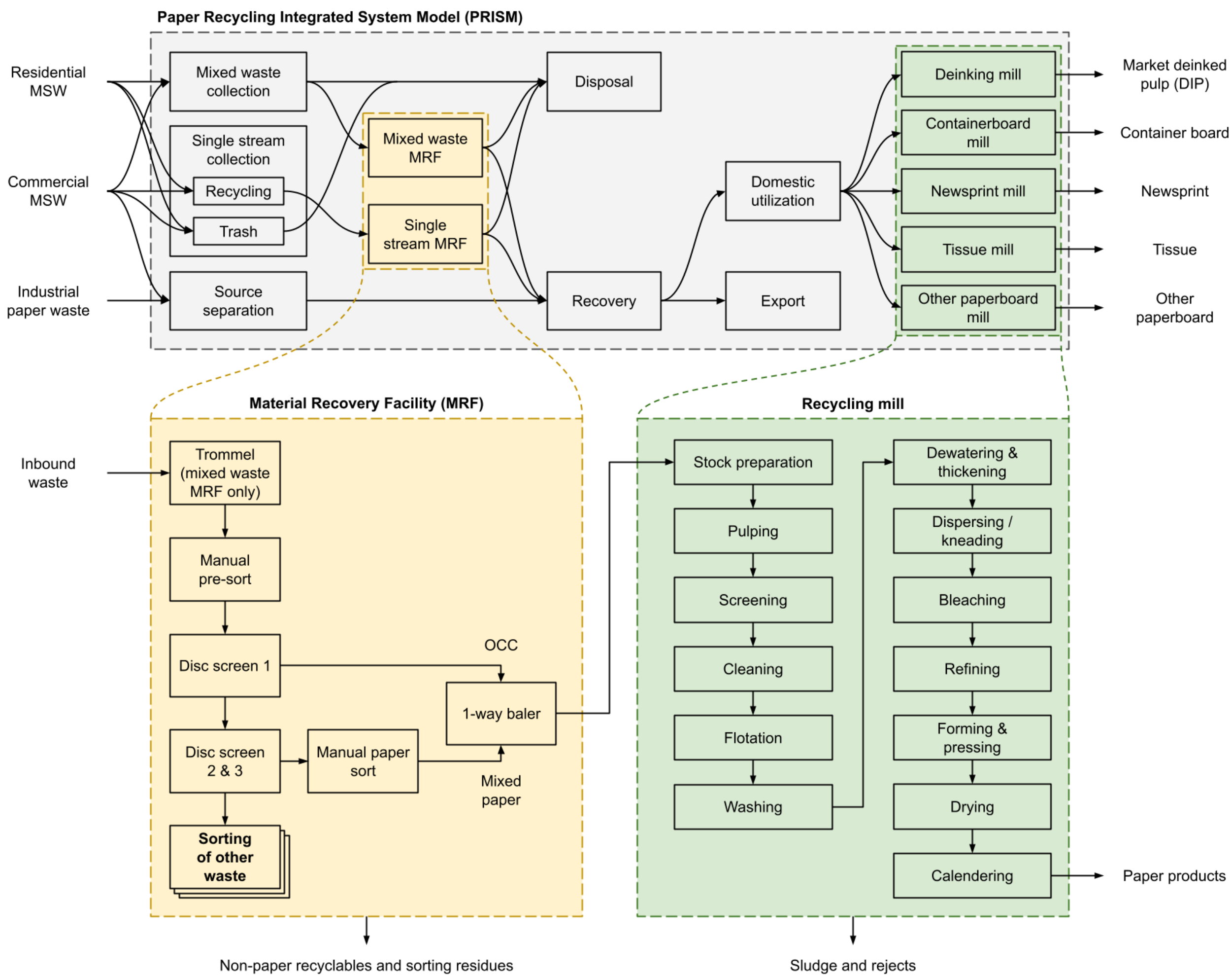


Figure 1. Modeling framework of the domestic paper recycling system, adapted from previous studies (Damgacioglu et al., 2020; Holik, 2009; Pressley et al., 2015). *Disc screens are used to sort OCC, newspapers and magazines, and other papers in order. A disc screen is an inclined plane with disc spreading rods which can allow large materials travel over the top while smaller materials fall between the discs* (Pressley et al., 2015).

The PRISM is a technology-rich model that includes, for each unit process, a material transfer coefficient, an energy consumption coefficient, a GHG emission intensity, and economic cost factors (see Figure S2). Specifically, the material transfer coefficients of sorting and deinking technologies are related to sorting efficiency and cleaning efficiency, respectively. The constant values of energy coefficient and GHG coefficient for a specific unit process are used to calculate the total energy consumption and GHG emissions from the mass flow processed by the unit process. Cost factors (e.g., capital installation cost, fixed cost, variable cost, etc.) are used in the techno-economic analysis to estimate the production cost of a specific recycled paper product. Because of the high level of granularity, the PRISM can evaluate how and to what extent changes in process parameters, technologies, and operating practices could affect the system's economic and environmental performance. For example, the overall material efficiency of the recycling chain can be explained by the individual sorting and deinking technologies based on their material transfer coefficients. Similarly, the model can explain the contribution of individual processes (such as a MRF disc screen or a paper mill cleaning process) to the total GHG emissions and the costs of recycled paper products. The PRISM was built using Analytica software and is hosted on Analytica Cloud (Lumina Decision Systems, 2022). The model was made available to industrial and government partners.

2.2 Unit process equations

The PRISM consists of a waste management module and a mill module. The waste management module covers waste generation, collection, sorting, recovery, and trade. The residential and commercial MSW stream contains paper and other materials, whereas the industrial source supplies pre-sorted paper. The MSW goes to single-stream recycling (one bin for recycling and one bin for trash) or mixed collection (one bin for all waste). The recycling fraction from single-stream recycling is sorted in MRFs. Mixed waste (or even trash) may be sorted in a mixed waste MRF, but since this practice is very rare, the model functionality was not used. The recovered paper bales from MRFs are captured in a matrix that shows the fraction of four paper products, as well as contaminants, in three types of fiber bales (OCC, mixed paper, and pre-sorted). The bales are either transported to domestic recycling paper mills or exported to foreign countries. The residues of waste papers are mainly disposed of to landfills.

The governing equations for the material flows, energy consumption, GHG emissions, and costs for each MRF equipment (i) are presented in Eqs. 1–4, respectively.

$$M_{out,i} = M_{in,i} \times S_i \quad (1)$$

$$E_i = M_{in,i} \times \frac{RMC_i \times \frac{MCU_i}{100}}{\max throughput_i \times \frac{ECU_i}{100}} \quad (2)$$

$$CE_i = CI_e \times E_i \quad (3)$$

$$C_i = P_e \times E_i + C_{fixed\ O\&M,i} + C_{capital,i} \quad (4)$$

The sorted material output from each equipment ($M_{out,i}$) is the product of the input to the equipment ($M_{in,i}$; equal to the sorted output from the preceding equipment, or $M_{out,i-1}$) and the sorting efficiency of the equipment (S_i); the sorting efficiency is a vector with values between 0 and 1 for every category of material managed by the MRF, representing the ratio of each material that gets sorted out by the equipment; the energy consumption of each equipment in kWh (E_i) is based on the equipment's rated motor capacity (RMC_i) in kW, percent of motor capacity utilized (MCU_i), max throughput in ton per hour, and percent of equipment capacity utilized (ECU_i); the GHG emissions from each equipment are the product of the energy consumption (E_i) and the fuel-specific emission factor (CI_e, for electricity or diesel); the cost of each equipment (C_i) is the sum of variable operations and maintenance (O&M) cost – represented in Eq. 4 as the product of energy price (P_e) and energy consumption (E_i) – fixed O&M cost, and amortized capital cost.

The mill module includes typical deinking unit processes for the five recycled paper grades. More details of the deinking unit processes can be found in Table S1. The governing equations for calculating the facility-level energy consumption and GHG emissions per unit of recycled paper product are expressed in Eqs. 5-9, where $EI_{product}$ and $CI_{product}$ are the energy intensity (GJ/oven-dry tonne (ODT)) and carbon intensity (kg CO_{2eq}/ODT) of unit recycled paper product, respectively; E_i and CE_i are the overall process energy consumption (GJ/h) and carbon emissions (kg CO_{2eq}/h) of the *i*th unit process, respectively; $EI_{process,i}$ and $CI_{process,i}$ are the energy coefficient (GJ/ODT) and carbon emission coefficient (kg CO_{2eq}/ODT) of the *i*th unit process, respectively; $EI_{process,i}$ is calculated based on the fuels and electricity consumed in each unit process; $CI_{process,i}$ is estimated based on the energy inputs and regional carbon emission factors of various energy sources in each unit process; Y_i and Y_n are the yields (ODT/h) of the *i*th and the final (*n*) unit process, respectively; $F_{in,i}$ is the feed flow rate (ODT/min) of the *i*th unit process, which is related to the pulp consistency in the *i*th unit process and the fiber content in the *i-1*th unit process; Con_i is the pulp consistency (%) of the feed flow in *i*th unit process; $M_{loss,i}$ is the fiber loss (ODT/h) in the i^{th} unit process, which is related to the contaminated material weight in the feed flow.

$$EI_{product} = \frac{\sum_1^n E_i}{Y_n} \quad (5)$$

$$E_i = Y_i \times EI_{process,i} \quad (6)$$

$$CI_{product} = \frac{\sum_1^n CE_i}{Y_n} \quad (7)$$

$$CE_i = Y_i \times CI_{process,i} \quad (8)$$

$$Y_i = F_{in,i} \times Con_i \times 0.01 - M_{loss,i} \quad (9)$$

$$C_{production,j} = \frac{C_{capital,j}+C_{fixed,j}+C_{utility,j}+C_{landfill,j}+C_{labor,j}+C_{tran,j}+C_{indirect,j}}{Y_n \times 8000} \quad (10)$$

The revenue of a MRF is challenging to estimate with limited available data of commodity market prices because it depends on a variety of recovered products (e.g., plastics, paper, metal, etc.). Moreover, considering collection and sorting are rarely profitable but require waste generators or local governments to cover the difference between, an increase in profitability will be expressed as a reduction in the production cost of bales. This study assumes the prices of virgin paper commodities is break even to the costs of the virgin ones. Similarly, an increase in profitability for recycling paper mills will be expressed as a reduction in production cost of recycled paper products.

The production cost of a specific recycled paper product is expressed in Eq. 10, where $C_{production,j}$ is the manufacturing production cost of a specific recycled paper product *j*; $C_{capital,j}$ is the annual amortized capital investment cost of equipment; $C_{fixed,j}$ and $C_{utility,j}$ are annual fixed cost and variable utility cost of a recycling paper mill for *j* paper product, respectively; $C_{landfill,j}$, $C_{labor,j}$, and $C_{tran,j}$ are annual landfill costs, labor costs, and transportation costs of a recycling paper mill for *j* paper product; the average transportation distance between MRFs and recycling paper mills is assumed to be 194 km (Tomberlin et al., 2020); $C_{indirect,j}$ is other indirect costs including operating supervision and maintenance cost (50% of total labor cost), fringe benefits (35% of total labor cost), and property tax and insurance (3% of total capital investment). A recycling paper mill is assumed to operate 8,000 hours per year.

The national average mill performance is estimated by the weighted average of energy consumption, GHG emissions and production cost for each recycled paper product based on the production technology share of each unit process (see Table S2 for detailed data). For example, the most conventional refining technology (96% share of total production capacity) used in container board manufacturing is high-consistency refining, and the remaining is low-consistency refining. Therefore, the average national energy intensity of refining technology for container board is calculated by the sum of energy intensities of two refining technologies weighted by the corresponding the production share of each technology. The national average energy intensity and the total national energy consumption of each recycled paper product are calculated by Eqs. 11 and 12, respectively, where $EI_{NA,j}$ and $EC_{total,j}$ are the national average energy intensity of unit j paper product and total national energy consumption of j paper product, respectively; $EI_{z,j}$ is the energy intensity of z process technology used in the ith unit process; $T_{z,j}$ is the national production technology share of z process technology used in the ith unit process; $Bale_{input,j}$ is the total recovered bale weight input for j paper product; YE_j is the fiber yield efficiency of j paper product (see TableS3 for detailed data of bale input and fiber yield efficiency). The national GHG emissions and production costs are calculated using the same approach.

$$EI_{NA,j} = \sum_{1}^{n}(EI_{z,i} \times T_{z,i}) \quad (11)$$

$$EC_{total,j} = EI_{NA,j} \times Bale_{input,j} \times YE_j \quad (12)$$

The results of energy use and GHG emission for unit processes at MRFs and unit processes at recycling paper mills are summed up to estimate the total energy consumption and GHG emissions for recycled paper products.

2.3 Data collection and processing

The PRISM was populated by a dataset representing the 2018 U.S. paper recycling system. It contains materials, energy, emissions, and cost data for all unit process technologies. For the waste management module, the data includes the waste generation quantities and transfer coefficients for collection and sorting (see Table S4), energy and cost factors for collection and disposal processes (see Table S5), and energy and cost factors for the MRF sorting processes (see Table S6). The transfer coefficients for the MRF processes were derived from the MSW sorting results reported by Damgacioglu et al. (Damgacioglu et al., 2020).

For the mill module, technology data for existing and emerging unit process technologies installed at recycling paper mills were collected from various sources, including technical reports, peer-reviewed studies, and equipment manuals (see Table S7). Other data such as energy and carbon emission intensities of virgin pulp-based paper production were collected from peer-reviewed studies (see Table S8). Data on energy prices (e.g., natural gas and electricity prices), grid electricity emission factors, labor cost, and water prices (see Table S9 in the SI) were collected from national published databases. Data on commodity prices of sorted bales were obtained from the Secondary Fiber Pricing database (Recycling Markets Limited, 2021).

2.4 Scenario design

This study presents three scenarios to assess the energy, carbon, and cost implications of increasing the collection of recyclable papers, improving sorting and reprocessing, and expanding technology capacity to achieve the REMADE national goals. The REMADE Institute has the ambition to increase the domestic paper recycling rate and recycled paper utilization rate by 15%. In addition, the REMADE institute proposed to develop advanced technologies to increase energy efficiency by 25% and reduce GHG emissions by 20% for unit paper product (REMADE Institute, 2022). The scenarios describe distinct strategies for achieving these goals, and are compared against the baseline performance in the year 2018. Table S10 summarizes the main differences between the scenarios; Table S11 lists the modelling assumptions for each scenario. The following paragraphs describe each scenario.

Scenario 1 (SC1): single-stream collection enhancement. Public investment realizes an increase in the availability of both residential (from 64% to 80%) and commercial (from 41% to 80%) single stream collection infrastructure. Local governments promote good recycling behavior: where recycling bins are available, they receive 80% of the recyclable papers, instead of just 26-60% of papers in the baseline (depending on grade). An alternative would be to not only expand single-stream recycling but also to sort mixed waste (or even the residual stream from single-stream recycling systems) in dedicated mixed waste MRFs (also known as “dirty MRFs”). However, none of the scenarios considers the use of mixed waste MRFs because operating mixed waste MRFs is very rarely economically viable.

Scenario 2 (SC2): technology improvement. Single-stream collection is expanded to the same extent as in SC1, but MRFs also invest in advanced sorting technologies. The sorting efficiency for disc screen unit processes increases by 10%, reflecting advancements such as robotic sorting, resulting in better quality bales with fewer contaminants. Recycled paper mills invest in emerging re-pulping and deinking technologies to improve the yield and quality of final recycled paper products. Recycling paper mills implement advanced deinking technologies that have either less fiber loss or higher cleaning efficiency. Table S8 lists details of new technologies implemented in specific unit processes for recycled paper products.

Scenario 3 (SC3): trade shift and capacity expansion. The demand for recovered paperboard rises dramatically in the domestic recycling system because of e-commerce packaging and delivery. In response, many recycling paper mills expand their processing capacity of recovered bales. All sorted paper bales are used for domestic recycling, compared to about a third being exported in the baseline. Meanwhile, the same developments occur as in SC1 and SC2: single-stream collection is enhanced and emerging technologies are implemented. Economic supply and demand dynamics were not considered in this scenario: it assumes a stable price for OCC and mixed paper bales from MRFs.

In summary, following actions and strategies are investigated in the model to achieve the national goals of paper recycling.

- SC1: 1) Residential single stream collection rate increases from 64% to 80%. Commercial single stream collection rate increases from 41% to 80%; 2) Everyone puts recyclable paper from households into curbside single stream recycling bins correctly: 80% sorting efficiency in the collection.
- SC2 (including actions in SC1): Implementing advanced sorting and reprocessing technologies at MRFs and recycling paper mills.
- SC3 (including actions in SC1 and SC2): All sorted bales are traded to recycling paper mills.

3. Results

3.1 Baseline system performance

This study estimates the system performance at both national and facility levels. The national-level outputs from the model include the quantities of recovered bales and different grades of final recycled paper products, overall paper RR, RIR, number of recycling paper mills required, energy consumption, GHG emissions, and total system cost. The facility-level performance of the U.S. domestic paper recycling in 2018 is evaluated in terms of energy consumption and GHG emission per unit of recycled paper product. For illustrative purposes, this study used Georgia regional data (see Table S7 for details) to estimate the facility level results since Georgia has the largest paper production capacity in the U.S. (Ince et al., 2001).

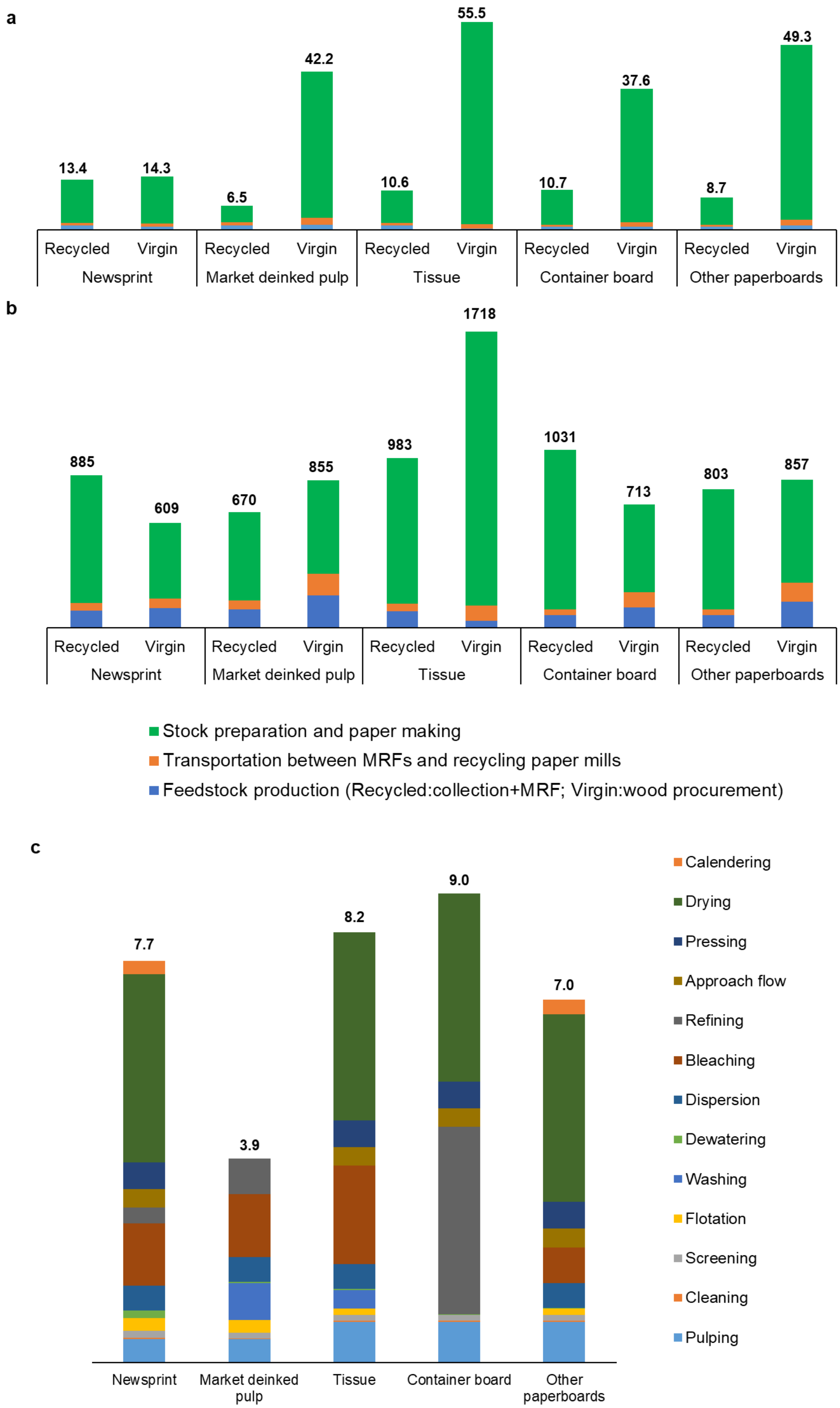
Table S12 summarizes the national-level results. The PRISM estimates that the domestic paper recycling rate amounted to 66.4%, which is consistent with the estimate from American Forest and Paper Association (AF&PA) (American Forest & Paper Association, 2021). The recyclable paper input rate was around 20%, suggesting only a small proportion of domestically produced paper is from recovered paper in 2018, with the remaining inputs (nearly 116 million tonnes) mainly virgin pulp.

The total quantity of recycled paper products was estimated at nearly 22 million tonnes, 89% of which were used to produce container boards, including corrugating medium and linerboards. The total system energy consumption is nearly 219 million GJ, resulting in 20.8 million tonnes of CO_{2eq} emissions, and 16.8 million tonnes for container boards only. This is close to a literature estimate of 13 million tonnes of CO_{2eq} (Tomberlin et al., 2020), suggesting that results from the PRISM are largely aligned with previous estimates. The MRF stage accounts for 12% and 11% of the total energy consumption and GHG emissions for the U.S. paper recycling system in 2018.

The total system cost of the U.S. paper recycling industry is $14.4 billion, to which recycling mills of container board and MRFs are the largest contributors. The U.S. Census Bureau (U.S. Census

Bureau, 2021) reported that the total cost of pulp, paper, and paperboard mills in 2018 was $70.1 billion with a total paper production of 71 million tonnes. In the baseline, the total cost of recycled paper processing mills is estimated to be $10.4 billion with a total paper production of 21.8 million tonnes. So, the modelled cost per tonne for the recycling sector is about half the cost per tonne reported for the entire paper sector. Whilst the figures are not directly comparable, they align with a trend for recycled products to be of lower quality and value.

Figure 2 compares the energy intensity and carbon emission intensity of the five recycled paper products with data from Tomberlin et al (2020) for paper products made from virgin fiber. The data presented by Tomberlin et al. is calculated by aggregated material inputs and GHG emission factors of materials for each paper grade at a mill level instead of unit process modeling used in the PRISM. All recycled paper products have lower energy consumption than virgin paper products, and most energy savings for recycled papers are from the downstream manufacturing processes (see Figure 2a). For instance, using recovered OCC to produce container boards only consumes one third of the energy for producing the same product made from virgin fiber. The upstream of recycled papers includes collection and sorting processes at MRFs, and wood procurement is the only upstream process for virgin fiber. Energy consumption of transportation differs little between papers made from virgin and recovered fiber.



a
13.4
14.3
6.5
42.2
10.6
55.5
10.7
37.6
8.7
49.3
Recycled
Virgin
Newsprint
Market deinked pulp
Tissue
Container board
Other paperboards
b
885
609
670
855
983
1718
1031
713
803
857
Stock preparation and paper making
Transportation between MRFs and recycling paper mills
Feedstock production (Recycled:collection+MRF; Virgin:wood procurement)
c
7.7
3.9
8.2
9.0
7.0
Newsprint
Market deinked pulp
Tissue
Container board
Other paperboards
Calendering
Drying
Pressing
Approach flow
Refining
Bleaching
Dispersion
Dewatering
Washing
Flotation
Screening
Cleaning
Pulping

Figure 2. The energy intensity (GJ/ODT) (a) and GHG emission intensity (kg CO_{2eq}/ODT) (b) per unit of products made from virgin (Tomberlin et al., 2020) *and recovered fiber. ODT stands for oven-dried tonnes. A breakdown of energy consumption (GJ/ODT) per unit of recycled paper products by unit process is provided in (c).*

For most grades, recycling saves emissions, but recycled newsprint and container boards were estimated to have higher GHG emissions than virgin paper products (see Figure 2b). In general, whilst recycling saves energy, it can rely more on fossil fuels, either directly or through the use of carbon-intensive electricity from the grid. In contrast, virgin pulp and paper mills extensively use biomass and biofuel (e.g., wood chips, hog fuel, and black liquor) instead of fossil fuels (e.g., coal and natural gas). For example, the biogenic CO_2 emitted by virgin container board accounts for nearly 70% of the total GHG emissions (Tomberlin et al., 2020). Besides the bio-based fuel use, virgin newsprint product is mainly mechanically pulped, which consumes less energy than chemical pulping process for the recycled newsprint product. Regarding the container boards, the recycled products consume more electricity than the virgin ones due to the intensive refining process for optimizing the fiber quality (AIKAWA GROUP, 2016). These findings are consistent with previous studies (Ma et al., 2022; van Ewijk et al., 2021) and EPA's Waste Reduction Model (WARM) (U.S. EPA, 2020b), which indicates an increase of 210 kg CO_{2eq}/short ton of office paper recycled in process emissions compared to the office paper with virgin feedstock. Pulp and paper industry will recycle more container boards as the cheaper feedstock cost and high demand for recycled container boards for packaging. But the industry needs to adopt emerging advanced technologies (e.g., powered by renewable electricity) to produce recycled container boards with less emissions.

The comparison in Figure 2 is consistent because neither the PRISM nor the estimation by Tomberlin et al. (Tomberlin et al., 2020) considers the impact of paper production on the forest carbon cycle. However, the total life cycle benefits may be different. The WARM suggests that the largest contribution to the GHG emission reduction by paper recycling is the forest carbon storage due to the reduced use of papers made from virgin fiber. Therefore, the GHG emissions savings for recycled paper products estimated by the PRISM could be more if taking the stored forest carbon into account.

Figure 2c) depicts the energy consumption by unit process for recycled papers. The most energy-intensive processes include drying, refining, pulping, and bleaching for reprocessing different recycled paper products. The major benefit from recycled paper utilization is the lower energy consumption in the pulping process compared to virgin paper production. However, the associated carbon benefits depend on energy use: about 30 % or more of the total energy consumption of recycled paper products is from electricity used in pulping, deinking, and refining processes. In contrast, the electricity use for virgin pulp and paper mills only accounts for 14% of the total energy use, and about 39% onsite energy use is from black liquor derived from the pulping process (U.S. Department of Energy, 2015).

3.2 Scenario analysis

3.2.1 National level

Figure 3 (more details in Table S12) indicates that all three scenario strategies can achieve the national goal of a 15% increase in the domestic paper RR. A comparison between SC1 and SC2 shows that an improvement in sorting efficiencies at MRFs only contribute a small increase in the overall recycling rate. One key reason is the lack of remaining bandwidth to increase sorting efficiency with improved sorting equipment. For instance, the current sorting efficiency of a disc screen for mixed papers could only increase from 85% to a theoretically perfect 100%. Relatedly, the use of advanced technologies in recycled paper processing mills has little impact on the RIR across scenarios because the contamination rates of bales from MRFs do not differ widely between scenarios owing to limited increase in sorting efficiency of facilities at MRFs. The yields of each reprocessing technology are affected by the amount of contamination in the bales. Therefore, the yields of recycled paper processing mills have small differences between scenarios. In SC2, the total energy consumption and GHG emissions are reduced due to advanced technology deployment compared to SC1, especially for container boards. In addition, container boards have the largest total system cost reduction due to savings in energy consumption of advanced technologies. Only SC3 achieves the national goal of a 15% increase in the RIR. The expansion in recycling requires additional recycled paper processing mills, with the majority of new plants built for producing container boards. The results of SC3 suggest that the total energy consumption and GHG emissions for achieving national paper recycling goals are around 327 million GJ and 24.5 million tonnes of $CO_{2\ eq}$, respectively. The annual cost to recycle these papers is estimated to be $21.9 billion, roughly 50% higher than the cost in the baseline scenario.

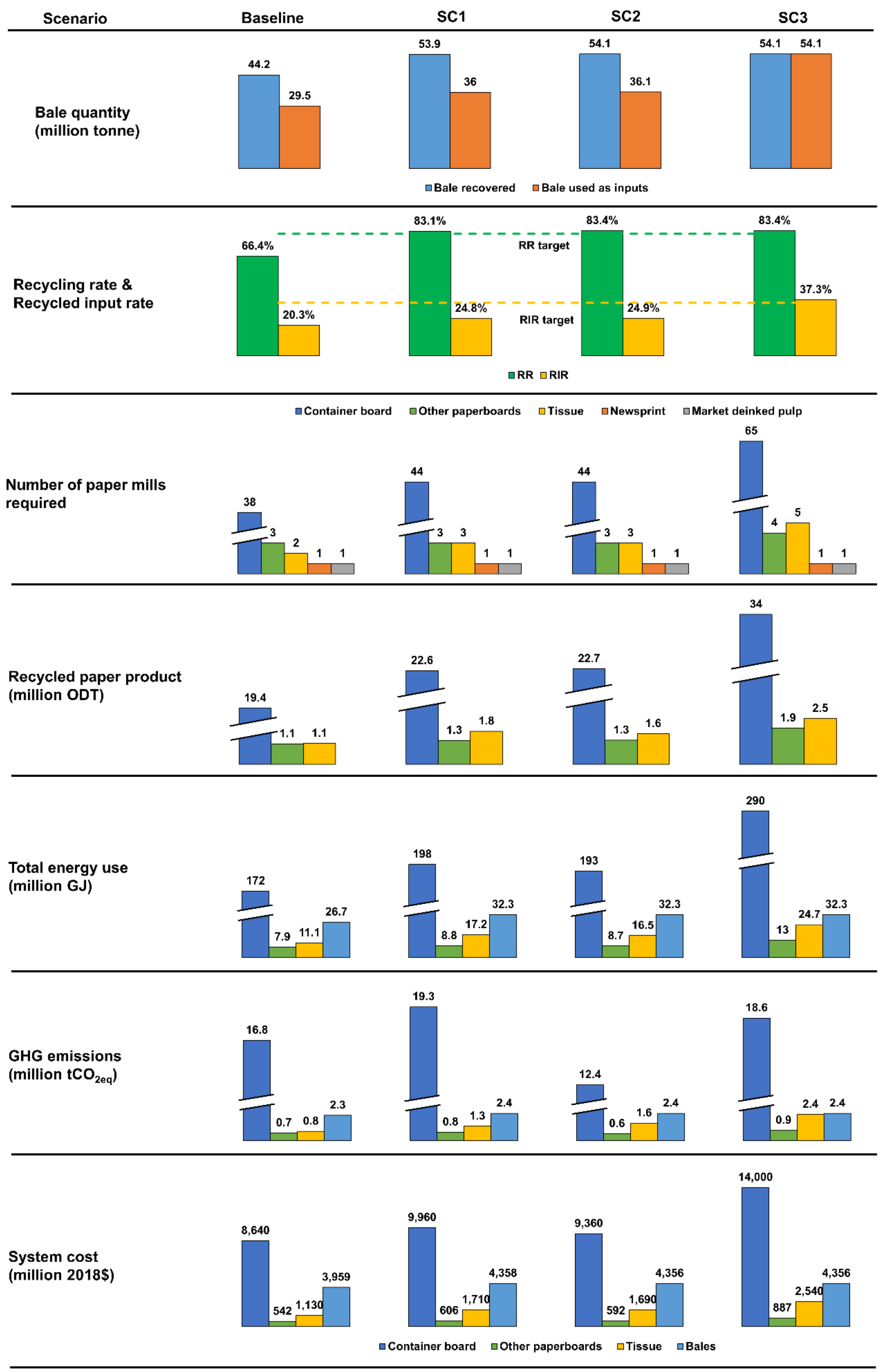

Scenario
Baseline
SC1
SC2
SC3
Bale quantity (million tonne)
44.2
29.5
53.9
36
54.1
36.1
54.1
54.1
Bale recovered
Bale used as inputs
Recycling rate & Recycled input rate
66.4%
20.3%
83.1%
24.8%
83.4%
24.9%
83.4%
37.3%
RR target
RIR target
RR
RIR
Container board
Other paperboards
Tissue
Newsprint
Market deinked pulp
Number of paper mills required
38
3
2
1
1
44
3
3
1
1
44
3
3
1
1
65
4
5
1
1
Recycled paper product (million ODT)
19.4
1.1
1.1
22.6
1.3
1.8
22.7
1.3
1.6
34
1.9
2.5
Total energy use (million GJ)
172
7.9
11.1
26.7
198
8.8
17.2
32.3
193
8.7
16.5
32.3
290
13
24.7
32.3
GHG emissions (million tCO_{2eq})
16.8
0.7
0.8
2.3
19.3
0.8
1.3
2.4
12.4
0.6
1.6
2.4
18.6
0.9
2.4
2.4
System cost (million 2018$)
8,640
542
1,130
3,959
9,960
606
1,710
4,358
9,360
592
1,690
4,356
14,000
887
2,540
4,356
Container board
Other paperboards
Tissue
Bales

Figure 3. National-level scenario analysis results. Notes: the RR is defined as the ratio of domestic recovered paper sorted at MRFs (excluding pre-sorted paper from industrial sources) to the total wastepaper in the MSW; the RIR is defined as the ratio of domestic recovered paper used as secondary feedstock for paper production over the total material inputs to the U.S. paper production. The results of newsprint and market deinked pulp (can be found in the SI) are not depicted due to the low quantities (less than 0.5 million metric tons) and corresponding contributions to the total energy consumption and GHG emissions.

3.2.2 Facility level

The facility-level results identify whether the national goals of reductions in energy consumption and GHG emissions per unit product can be achieved through advanced technology deployment and recycled material use. The results of mill process energy use in SC2 indicate that deploying advanced technologies is more energy efficient except for tissue (see Table S13). The advanced drying technology deployed for tissue production is through air drying, which can improve the tissue quality with advantageous properties (Stenström, 2020), but it has higher energy intensity and consumes more energy. In this study, recycled market deinked pulp has the most process energy savings by 87% compared to virgin pulp production. The aggregated energy use including process energy at MRFs and mills is also much lower compared to the energy use of paper products made from virgin fiber.

Only newsprint and container boards have higher GHG emissions after recycled paper processing mills implement the advanced technologies. Considering all processes within the cradle-to-gate scope, recycled container boards produced by advanced technologies have lower GHG emissions than container boards produced from virgin fiber (see Figure 4). Although recycled newsprint still has higher GHG emissions than newsprint produced from virgin fiber, the difference in GHG emissions reduces significantly in the cradle-to-gate scope. It should be noted that since a large proportion of energy consumption in the recycling paper mill is electricity, the GHG emissions of the electrical grid result in variations in different regions.

Most recycled paper products have a lower production cost in SC2 compared to the baseline scenario due to savings in energy cost. However, the product costs of newsprint and tissue are higher (see Table S13), which is attributed to the high capital equipment cost of advanced drying technologies (infrared drying for newsprint and air drying for tissue). The production cost also can be reduced by implementing heat recovery systems for primary energy savings. Many U.S. paper mills have installed heat recovery systems (e.g., combined heat power and cogeneration processes) to save energy use and cost in the pulping and drying processes and to reduce the total direct production cost (Ghosh, 2011; U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, 2002).

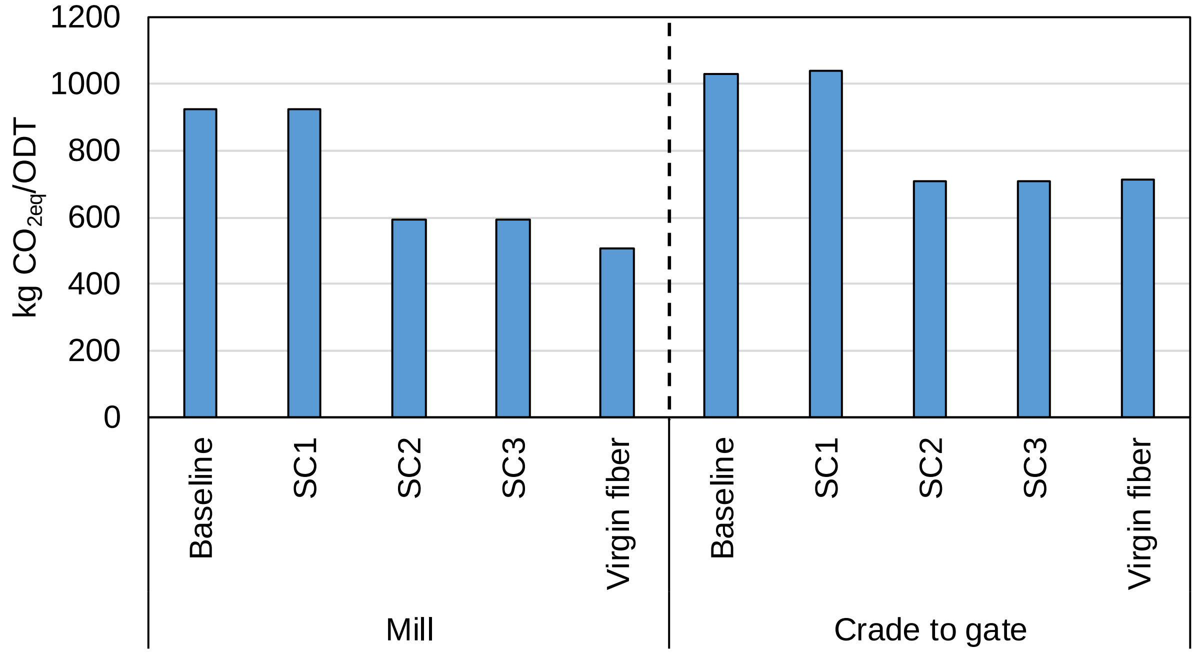


Figure 4. Mill process and cradle-to-gate process GHG emissions comparison between recycled and virgin container board production at the facility level.

4. Discussion

The findings in this paper suggest several strategies for the U.S. paper recycling industry to respond to China's import restrictions and achieve national recycling goals. The national goal of a 15% increase in recycling can be met through a 80% correct separation efficiency of recyclable papers from the residential recycling bins, together with an increase to 80% in the residential and commercial single-stream collection rates. Although this theoretical collection rate is much higher than the current situation, it is possible to achieve in reality and increasing the sorting rate of recyclable paper from the residential and commercial sources can significantly improve the domestic recycling rate. To answer the first question posed in this study, governments can take actions that boost recycling by enhancing education for local recycling programs, incentivize recycling behaviors, and improve materials management infrastructure with more consistent recycling program policies (U.S. GAO, 2020) and informative designs (Li et al., 2022). Moreover, emphasis on collection system improvement (e.g., dual- and multi-stream collection) could reduce contamination to a certain extent for recyclable papers, which will make recycling processes more efficient (Seldman, 2022).

An increase in U.S. domestic recycling has substantial energy and carbon benefits. However, for selected paper products, the PRISM suggests that GHG emissions from reprocessing recovered fibers might be higher compared to paper products made from virgin fiber based on the assumption that biogenic carbon emissions from biomass wastes used as fuels in paper mills are considered to be carbon neutral. This challenge may be met by further reducing the energy requirements of reprocessing and shifting to renewable energy supply. A shift to renewables may be achieved through decarbonization of the grid or the onsite generation of electricity and heat from renewables, potentially from biomass with combined heat and power (CHP). Electrification of drying technologies (e.g., infra-red drying) can also assist in a shift from fossil-based heat to renewable electricity. Moreover, building recycling paper mills in regions with a lower-emission electricity grid and lower cost of utilities can significantly decrease the total GHG emissions and production cost of recycled paper production (see Figure S3).

According to the EPA's national recycling strategies, there is a need to strengthen domestic markets for recyclable materials and recyclable products. A more robust domestic paper recycling market will provide more profitability to MRFs and recycling paper mills with greater resilience to market disruptions (U.S. EPA, 2021). Meanwhile, advanced sorting and reprocessing technologies can increase the quality and quantity of recycled paper products and save energy and GHG emissions. There are some technical and economic barriers for expanding recycled paper capacity. Technically, it still needs more advanced pulping and deinking technologies to reprocess mixed paper bales from MRFs for producing high-quality packaging paper (e.g., from newsprint to packaging) (Resource Recycling, 2022). The present study shows that considerable investments would be needed to expand the domestic processing capacity of recycled paper products. Announcement of a new mill might not guarantee it will be built due to the high capital investments (Northeast Recycling Council, 2022). Supportive policies, programs, initiatives, and incentives might be needed to facilitate the reutilization of recyclable papers and market expansion of recycled paper products (U.S. EPA, 2021). In addition, capacity expansion depends on overall demand for the final recycled products.

The PRISM considers the interactions between recyclable paper collection, MRF operations, and recycling paper mill manufacturing. The model structure and features have demonstrated to industrial operators from MRFs and paper recycling companies. The PRISM has been validated and refined based on advice from those industrial experts. Still, one of the major model limitations is the data paucity and quality of facility equipment cost. Since it is challenging to acquire real cost data for equipment installed at paper mills, the cost data we used are obtained from the prices of different equipment by searching on the manufacturing supplier website of Made-in-China (Focus Technology Co. Ltd, 2022). However, all data documented in the PRISM can be updated and adjusted by users to consider changes in parameters including energy efficiencies of emerging advanced technologies, equipment cost, energy prices, and so forth.

Future work may expand the model with an analysis of GHG emissions from forest management of virgin pulp production. This improvement can provide more robust results of GHG savings derived from recycled paper utilization compared to virgin fiber-based pulp and paper. In addition, GHG emissions from waste management for bale wastes and sludge at recycling paper mills (e.g., CH_4 emission from sludge landfills) were estimated in the PRISM but not presented in this study owing to there is a lack of related data for virgin pulp production to be compared for validation.

This assumption is consistent with WARM, which also left out the additional GHG emissions from disposal of paper sludge at paper mills owing to the complexity of analyzing those second-order effects and the lack of data (U.S. EPA, 2020b).

In future study, more scenarios considering the MRF processing capacity and price volatility in recovered bales due to some disruptions (e.g., an increase in domestic recycled package paperboard caused by COVID-19) in the supply chain could also be simulated to provide more practical solutions for improving the U.S. paper recycling system. The PRISM will be open to researchers upon request for conducting a lot of relevant scenario analysis at both the national and facility level.

5. Conclusion

This study developed the PRISM to simulate the 2018 U.S. domestic paper recycling system by characterizing system relationships between collection, sorting, and recycling paper mill operations. The technology-rich model enables an exploration of the effects of technology improvements on key indicators related to energy use, CO_2 emissions, total production cost, and system cost. The PRISM was used to assess three pathways for achieving the national goal of increasing the domestic paper recycling rate. The results suggest that an increase the single-stream collection rate and improved sorting behavior by residents can achieve the increase in domestic paper recycling rate by 15%. A trade shift of sorted bales from export to domestic recovery can also increase the recovered paper utilization rate by 15%, but would require costly capacity expansion of domestic recycling paper mills to process the additional 24.5 million tonnes of sorted bales. The implementation of advanced technology could enable MRFs and paper mills to produce recycled paper products with less energy and producing fewer GHG emissions, with some exception because of the current reliance of recycling on fossil fuels. Government and industry decisionmakers can use the PRISM to identify sustainable strategies for achieving the national recycling goals and a shift towards a circular economy by understanding the tradeoffs between system environmental and economic performance.

6. Acknowledgements

This research was supported by the REMADE Institute Project #18-02-SA-02 (10.4). In addition, we would like to express our appreciation to Bret Biggers, David Wagger, and Robin Wiener from ISRI for their support in arranging interactions with ISRI member companies and recycling industry experts, providing feedback and inputs on project outputs, and conducting valuable industry surveys. We also want to thank Dr. Elsa Olivetti and Jacqueline Ewuraesi from MIT for sharing their data with us. Finally, we wish to thank those industrial experts who provided valuable project advice.

References

AIKAWA GROUP, 2016. Introduction to Stock Prep Refining [WWW Document]. URL https://aft-global.com/sites/default/files/resources/docs/files/2017-03/EB-050-ENA4_FineBar Training Manual 2016_A4.pdf

American Forest & Paper Association, 2021. Paper Recycling Graph [WWW Document]. URL https://www.afandpa.org/statistics-resources/paper-recycling-graph (accessed 7.18.22).

Damgacioglu, H., Hornilla, M., Bafail, O., Celik, N., 2020. Recovering value from single stream material recovery facilities – An outbound contamination analysis in Florida. Waste Management 102, 804–814. https://doi.org/10.1016/j.wasman.2019.11.020

Focus Technology Co. Ltd, 2022. Made-in-China [WWW Document]. URL https://www.made-in-china.com/

Ghosh, A.K., 2011. Fundamentals of Paper Drying-Theory and Application from Industrial Perspective, Evaporation, Condensation and Heat transfer.

Heath, L.S., Maltby, V., Miner, R., Skog, K.E., Smith, J.E., Unwin, J., Upton, B., 2010. Greenhouse gas and carbon profile of the U.S. forest products industry value chain. Environ Sci Technol 44, 3999–4005. https://doi.org/10.1021/es902723x

Holik, H., 2009. Recycled Fibre and Deinking, Papermaking Science and Technology.

Ince, P.J., Li, X.L., Zhou, M., Buongiorno, J., Reuter, M.R., 2001. United States paper, paperboard, and market pulp capacity trends by process and location, 1970-2000, Research Paper Forest Products Laboratory, USDA Forest Service.

ISRI, 2020. Recycling Industry Yearbook 2019.

Krones, J.S., 2016. Accounting for Non-Hazardous Industrial Waste in the United States. Materials Science and Engineering, MIT.

Leon, J., Aliaga, C., Boulougouris, G., Hortal, M., Marti, J.L., 2015. Quantifying GHG emissions savings potential in magazine paper production: A case study on supercalendered and light-weight coated papers. J Clean Prod 103, 301–308. https://doi.org/10.1016/j.jclepro.2014.03.008

Li, Y., Zambrano, F., Wang, Y., Marquez, R., 2022. How China's foreign waste ban will reshape the U.S. recycling supply chain: Economic and environmental considerations towards a circular economy oriented paper recycling industry. Bioresources 17, 3178–3201. https://doi.org/10.15376/biores.17.2.3178-3201

Lumina Decision Systems, 2022. Analytica.

Ma, G., Tian, H., Xiao, Y., Lu, X., Zhang, L., Liu, X., 2022. Environmental assessment of recycling waste corrugated cartons from online shopping of Chinese university students. J Environ Manage 319, 115625. https://doi.org/10.1016/j.jenvman.2022.115625

Man, Y., Han, Y., Li, J., Hong, M., Zheng, W., 2019. Life cycle energy consumption analysis and green manufacture evolution for the papermaking industry in China. Green Chemistry 21, 1011–1020. https://doi.org/10.1039/c8gc03604g

Northeast Recycling Council, 2022. NERC Releases Update on Increased Capacity to Use Recycled Paper [WWW Document]. URL https://nerc.org/news-and-updates/press-releases/?article=2272

Ozalp, N., Hyman, B., 2006. Energy end-use model of paper manufacturing in the US. Appl Therm Eng 26, 540–548. https://doi.org/10.1016/j.applthermaleng.2005.07.032

Pressley, P.N., Levis, J.W., Damgaard, A., Barlaz, M.A., DeCarolis, J.F., 2015. Analysis of material recovery facilities for use in life-cycle assessment. Waste Management 35, 307–317. https://doi.org/10.1016/j.wasman.2014.09.012

Recycling Markets Limited, 2021. Secondary Fiber Pricing [WWW Document]. URL https://www.recyclingmarkets.net/secondaryfiber/index.html

REMADE Institute, 2022. REMADE INSTITUTE: IMPACT REPORT 2021 [WWW Document]. URL https://remadeinstitute.org/remade-impact-report

Resource Recycling, 2022. Editor's Perspective: First look at a retooled paper mill [WWW Document]. URL https://resource-recycling.com/recycling/2022/10/25/editors-perspective-first-look-at-a-retooled-paper-mill/

Seldman, N., 2022. Single Stream/Dual Stream: Contending Approaches to Recycling in the US [WWW Document]. Institute for Local Self-Reliance. URL https://ilsr.org/single-stream-dual-stream-contending-approaches-to-recycling-in-the-us/

Sevigné-Itoiz, E., Gasol, C.M., Rieradevall, J., Gabarrell, X., 2015. Methodology of supporting decision-making of waste management with material flow analysis (MFA) and consequential life cycle assessment (CLCA): Case study of waste paper recycling. J Clean Prod 105, 253–262. https://doi.org/10.1016/j.jclepro.2014.07.026

Silva, D.A.L., Raymundo Pavan, A.L., Augusto De Oliveira, J., Ometto, A.R., 2015. Life cycle assessment of offset paper production in Brazil: Hotspots and cleaner production alternatives. J Clean Prod 93, 222–233. https://doi.org/10.1016/j.jclepro.2015.01.030

Stenström, S., 2020. Drying of paper: A review 2000–2018. Drying Technology 38, 825–845. https://doi.org/10.1080/07373937.2019.1596949

Tomberlin, K.E., Venditti, R., Yao, Y., 2020. Life cycle carbon footprint analysis of pulp and paper grades in the united states using production-line-based data and integration. Bioresources 15, 3899–3914. https://doi.org/10.15376/biores.15.2.3899-3914

U.S. Census Bureau, 2021. Table: 2018-2020 - Statistics for All Manufacturing by State.

U.S. Department of Energy, 2015. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing 108.

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, 2002. Steam System Opportunity Assessment for the Pulp and Paper, Chemical Manufacturing, and Petroleum Refining Industries.

U.S. EPA, 2021. National Recycling Strategy 1–68.

U.S. EPA, 2020a. Advancing Sustainable Materials Management: 2018 Fact Sheet. Washington, DC.

U.S. EPA, 2020b. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM) Management Practices Chapters.

U.S. GAO, 2020. Building on existing federal efforts could help address cross-cutting challenges [WWW Document]. URL https://www.gao.gov/assets/gao-21-87.pdf

van Ewijk, S., Park, J.Y., Chertow, M.R., 2018. Quantifying the system-wide recovery potential of waste in the global paper life cycle. Resour Conserv Recycl 134, 48–60. https://doi.org/10.1016/j.resconrec.2018.02.026

van Ewijk, S., Stegemann, J.A., Ekins, P., 2021. Limited climate benefits of global recycling of pulp and paper. Nat Sustain 4, 180–187. https://doi.org/10.1038/s41893-020-00624-z