NCASI

White Paper

WP-23-03

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RECYCLABILITY
OF
PAPER AND PAPERBOARD

NCASI WHITE PAPER
OCTOBER 2023

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Cite this report as:

NCASI. 2023. *Recyclability of paper and paperboard.* White Paper (WP-23-03). Cary, NC: National Council for Air and Stream Improvement, Inc.

RECYCLABILITY OF PAPER AND PAPERBOARD

EXECUTIVE SUMMARY

Paper and paperboard is the largest municipal solid waste (MSW) component recycled within the United States, and represents 67% of all MSW components recycled. The industry continues to strive to increase the collection and recycle of generated paper and paperboard, and to increase the utilization rates of recovered fiber for the manufacture of paper and board products. This white paper provides information on fiber longevity, fresh fiber requirements for a functioning fiber cycle, age distribution of products, average number of times fiber can be recycled, utilization rates, and market changes and challenges affecting recyclability for the US paper and paperboard sector.

The average and maximum fiber longevity in the US have increased as the market has shifted from grades with lower utilization rates of recovered paper, such as printing and writing, to grades with higher utilization rates, such as containerboard. The average age distribution of fiber products has also increased as domestic utilization rates have increased. The utilization rate in the US has increased from 36.9% in 2012 to 43.8% in 2021, and may approach 50% as announced containerboard capacity comes online to create more demand for collected recovered paper that is currently exported. Recovery rates in the US have remained steady over the last decade, averaging 66% between 2011 and 2021.

KEYWORDS

recycled fiber, recycled fibre, recyclability, utilization rate, recovery rate, sustainability

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Abbreviations

DIP	Deinked Pulp
MFA	Mean Fiber Age
MNU	Mean Number of Future Uses
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
OCC	Old Corrugated Containers
TAD	Through Air Drying

RECYCLABILITY OF PAPER AND PAPERBOARD

1.0 Introduction

Approximately 292 million short tons of municipal solid waste (MSW) were generated in 2018[1] in the United States (USEPA 2020). Sixty-nine million short tons of municipal solid waste were recycled in 2018. Of this amount, paper and paperboard represented 46 million short tons. Paper and paperboard is the largest MSW component recycled within the US, and represents 67% of all MSW components recycled, as illustrated in Figure 1 below.

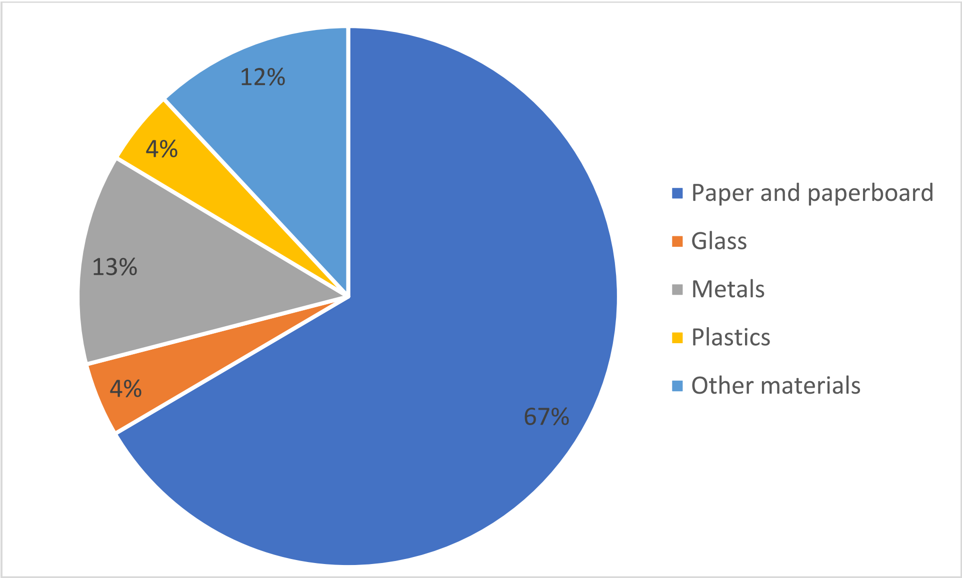

Figure 1. *Municipal solid waste components recycled in 2018 within the United States*

The industry continues to strive to increase the collection and recycle of generated paper and paperboard and to increase the utilization rates of recycled fiber for the manufacture of paper and board products. One of the American Forest and Paper Association's (AF&PA) 2030 sustainability goals is to "Increase the utilization rate of recycled fiber and wood residuals in manufacturing across the industry to 50 percent."[2] This white paper provides sustainability information related to recycled fiber such as fiber longevity, fresh fiber (sometimes referred to as "virgin fiber") requirements for a functioning fiber cycle, age distribution of products, average number of times fiber can be recycled, utilization rates, and market changes and challenges affecting recyclability.

[1] The latest year in which statistics are available from USEPA.
[2] https://www.afandpa.org/2030

2.0 Definitions

Consistent definitions of key terms related to the recovery and reuse of paper and board materials are essential to ensure comparability of recycling statistics among regions. Ervasti et al. reviewed terms and definitions related to paper recycling and determined that no uniform set of definitions related to paper recycling exists (Ervasti et al. 2015). Definitions vary by geographical region and have varied over time, e.g., CEPI[3] changed their definition of paper recycling to include net exports of paper products in 2006. Definitions used throughout this white paper are based on AF&PA definitions (AF&PA 2022). AF&PA definitions have been adopted by USDA in publications (Skog et al. 2011).

Total Recovered Paper = (Consumption of recovered paper at domestic paper and board mills) + (other uses of recovered paper) + (recovered paper exports) + (consumption of paper to produce recycled pulp for export) – (recovered paper imports)

Recovery Rate = Total Recovered Paper / New Supply of Paper and Paperboard (including wet machine board and construction grades)

Utilization Rate = Consumption of recovered paper at domestic paper and board mills / New Supply of Paper and Paperboard (including wet machine board and construction grades)

New Supply of Paper and Paperboard = Domestic production + imports of products – exports of products

The difference between recovery rate and utilization rate is primarily due to the influence of international trade in recovered paper. For a country like the United States whose exports of recovered paper are greater than imports of recovered paper, the recovery rate will be larger than the utilization rate. The US had exports of recovered paper of approximately 18 million short tons in 2021 compared to imports of approximately one million short tons. It is important to note that total recovered paper includes recovered paper and board products that enter the US with packaging. There is a certain amount of recovered paper that is used outside of the paper and board industry, i.e., used for composting, insulation, molded pulp, etc. Estimates of the utilization of recovered paper outside of the paper and board industry are between 4.8 and 7.4% of total recovered paper use (COST E48 2010).

3.0 The Fiber Cycle

Fresh fiber and recycled fiber are part of a single integrated wood fiber system. Recycled fiber would not exist if fresh fiber were not harvested and used to produce paper and paperboard products that are the fiber source for recycled paper products (WBCSD 2015). Regional fiber cycles, i.e. distinct paper and paperboard product and consumption regions such as Europe, United States, South America, Japan, etc. tend to operate in a way that maximizes the value of the use of fresh and recycled fiber available, i.e., fresh fiber may be used more prominently in chemical pulping processes to produce products with stringent strength and brightness requirements while recycled fiber may be used more prominently for packaging products that may have lower brightness requirements and marginally lower strength requirements than fresh fiber based products.

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[3] CEPI: Confederation of European Paper Industries

Figure 2 shows the domestic fiber cycle with the important operational steps. The aim of this white paper is to provide context and numerical results around each of the operational steps within the US fiber cycle, along with their influence on recyclability of paper and paperboard within the US.

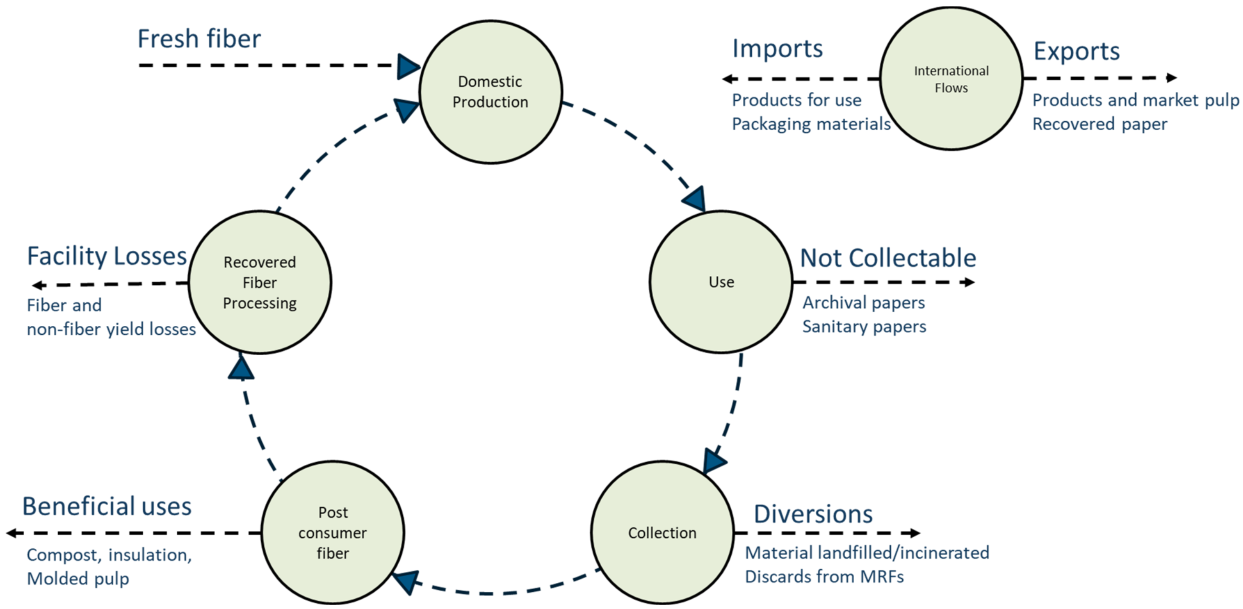

Figure 2. *Domestic fiber cycle*

4.0 Results

Important sustainability questions related to the recyclability of paper and paperboard include:

- What is the longevity of the fiber cycle (the amount of time the regional fiber cycle would operate in the absence of fresh fiber)?
- What is the required amount of fresh fiber to maintain current operating levels of paper and paperboard products?
- How many times can fiber be recycled?
- What is the age distribution of fibers in the current fiber cycle?
- What is the maximum utilization rate for recycled fibers in the US?

Context and numerical results, where possible, are provided for each of these questions within this section.

4.1 Fiber Longevity

Metafore presented a simple mass balance model with associated equations to calculate fiber longevity and fresh fiber requirements (Metafore 2006). Results using the model based upon 2005 data were originally presented by Metafore (2006) and NCASI updated results using the same approach with 2016/2017 data (NCASI 2019). Definitions, equations, and data sources and numbers used with the Metafore model are provided in Appendix A. Based upon 2021 data, the weighted average fiber cycle longevity is 7.3 months for the US paper and board industry, meaning that the US fiber cycle would be devoid of fiber in about seven months without the constant input of fresh fiber. When using maximum utilization rates for major grades, the weighted average fiber cycle longevity is 12.3 months. Table 1 shows the increase in average and maximum fiber longevity as the market has shifted from grades with lower utilization rates (newsprint and printing & writing) to higher utilization rates (containerboard and tissue), as well as improved grade utilization rates.

Table 1. *Changes in fiber longevity with changing production mix*

Data Year	Fiber Longevity (weighted average, months)	Fiber Longevity (maximum, months)
2005[a]	4.0	8.3
2016/2017[a]	6.1	10.9
2021	7.3	12.3

[a] North America

4.2 Fresh Fiber Requirements

With the Metafore mass balance model fresh fiber requirements can be estimated to maintain current operating levels. Based upon 2021 data, at current utilization rates, 62% of the fiber cycle needs are met with fresh fiber input. At maximum utilization rates, fresh fiber will still be required to meet half of the total fiber cycle requirements. Table 2 shows the decrease in fresh fiber requirements over time. Fiber cycle longevity calculations are based upon annual statistics and are therefore conservative because they assume that there is a year's worth of product inventory that can be used to supply the fiber cycle. In actual practice, fiber inventories are much less than a year's supply of inventory, so the fiber cycle would cease to function more rapidly than is shown in Table 2 if fresh fiber were eliminated from the fiber cycle.

Table 2. *Fresh fiber requirements as current and maximum utilization rates*

Data Year	Fresh fiber requirements, current utilization rate (%)	Fresh fiber requirements, maximum utilization rate (%)
2005[a]	72%	60%
2016/2017[a]	66%	53%
2021	62%	50%

[a] North America

4.3 Age Distribution of Products

4.3.1 *Mean Fiber Age and the Number of Future Material Uses*

Knowledge of the age distribution of products with recycle content is important because there is a link between the number of times a fiber can be processed before excessive degradation of activity of the fiber renders the fiber unsuitable for paper products. Steady state material balance models have been developed to calculate the likely age distribution (a measure of the number of times a fiber has been reprocessed) of paper and paperboard products containing recycled fiber (Ackermann et al. 2000; Cullinan 1992). Realistic regional fiber flow models require extensive data for parameterization; data requirements include information on the type and amount of paper recovered, product destination for recovered fiber, production amounts for product types, and regional imports and exports. Regional fiber flow models have been developed for the European market (Meinl et al. 2016) and for the US market (Chang et al. 2019). Different data quality and availability levels exist for various regions of the world and data from one region is often in incompatible form with other regions. In addition, there is a dynamic nature to fiber flow. It takes time for fiber to diffuse from fresh fiber products through use, collection, and repurposing into recycled fiber products. Figure 3 shows a simple one-parameter model that is useful for explaining aspects of real fiber cycles. With this model there is one parameter, *a*, the recovered paper utilization rate. Meinl et al. used the one parameter model to analyze recycling in different regions of the world and introduced the concepts of mean fiber age (MFA) and mean value of the distribution of the number of future uses (MNU) (2017), which are key parameters for more realistic and complex models like the European Fiber Flow Model (Meinl et al. 2016) and AF&PA-MIT Fiber Flow Model (Chang et al. 2019).

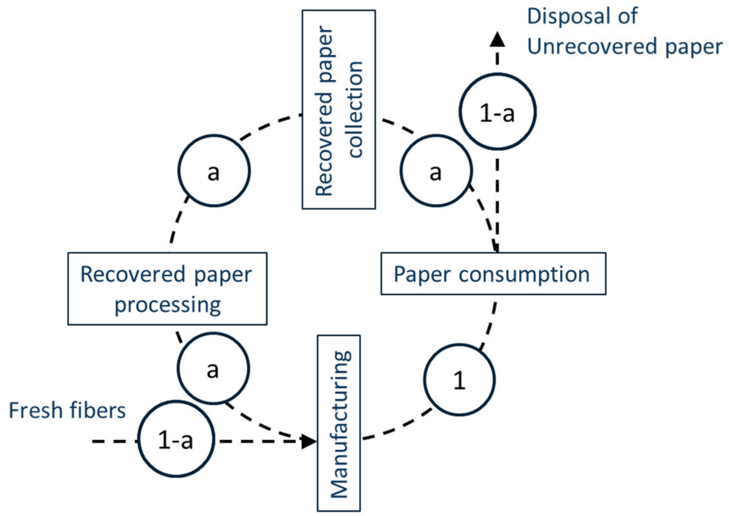

Figure 3. *One parameter model[4] for recycled fiber*

Figure 4 shows the age distribution of a hypothetical product as a function of recovered fiber content using the one-parameter model (Figure 3) that elucidates a number of important points that are reflected within real products.

- At recovered fiber contents of 50% or less, the average number of fiber generations within a product is low, but increases rapidly with increased utilization rate.
- At a recovered fiber content of 75%, fiber of generations older the three make up over 30% of the total product fraction.

[4] Assumptions for the one-parameter model: (1) identical recovered paper utilization rate for all paper grades, (2) No paper export and import, (3) No recovered paper export or import, (4) No yield losses in recovered paper processing or collection (Ackermann et al. 2000; Hunold 1997).

- At a recovered fiber content of 75%, up to fourteen generations of fiber may be present within a product containing recycle fiber.
- Even in regions with high recovery and utilization rates, imported products with lower age distribution that make their way into the domestic recycle stream will effectively reduce the average age distribution of recycled material processed domestically.

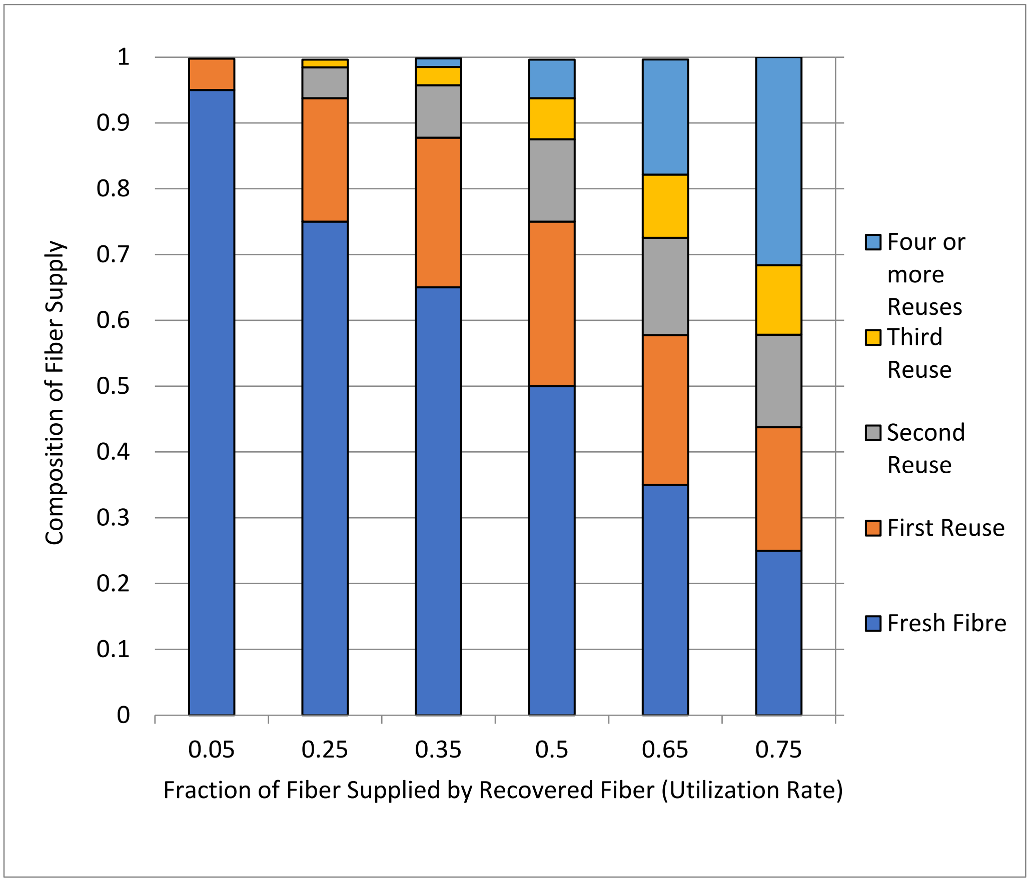

Figure 4. *Age distribution of a product as a function of utilization rate*

Figure 5 shows the mean fiber age as a function of utilization rates using the one-parameter model. Mean fiber age is a representation of the number of uses of fiber within products. A paper product made entirely of fresh fiber would have a mean fiber age of 1.0. At utilization rates greater than 50%, the mean fiber age increases rapidly, meaning fibers that have been recycled multiple times are present within products. Figure 6 shows the total number of fiber uses in a product's lifetime[5] as a function of utilization rate using the one-parameter model. As with mean fiber age, the total number of fiber uses in a product's lifetime increases rapidly at utilization rates greater than 50%. Related modeling and laboratory studies on the average number of times fiber can be recycled is covered in the next section. As long as the mean total number of lifetime fiber uses is less than the average number of times fiber can be recycled, theoretically there is no inherent fiber quality degradation issues that would limit additional fiber recycle.

[5] Total number of fiber uses in a product's lifetime is calculated as: MFA + MNU -1 (Meinl et al. 2017)

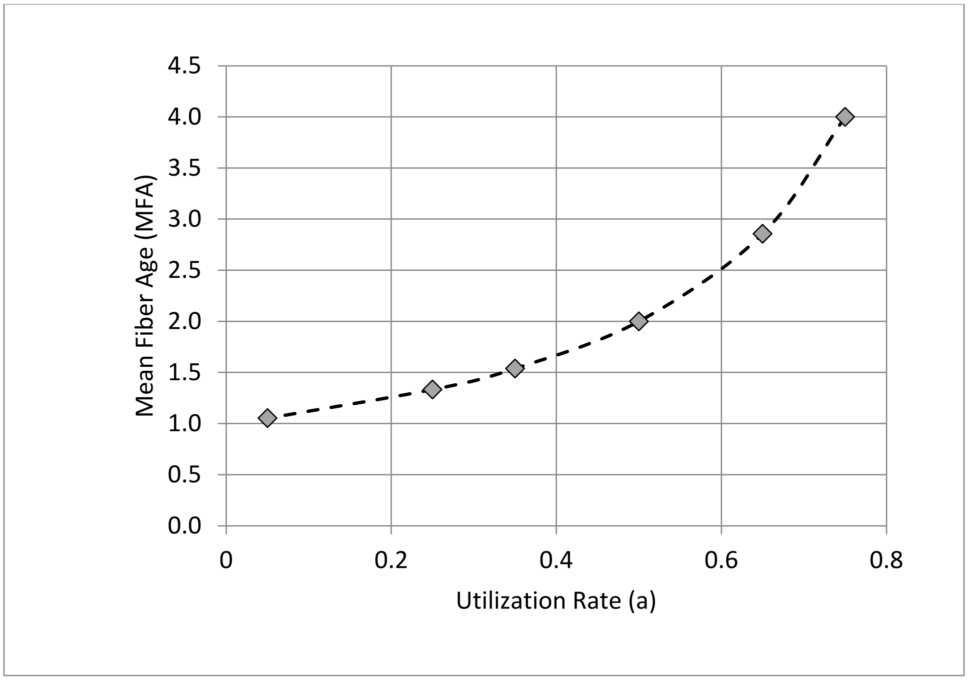

Figure 5. *Mean fiber age as a function of utilization rate with the one-parameter model*

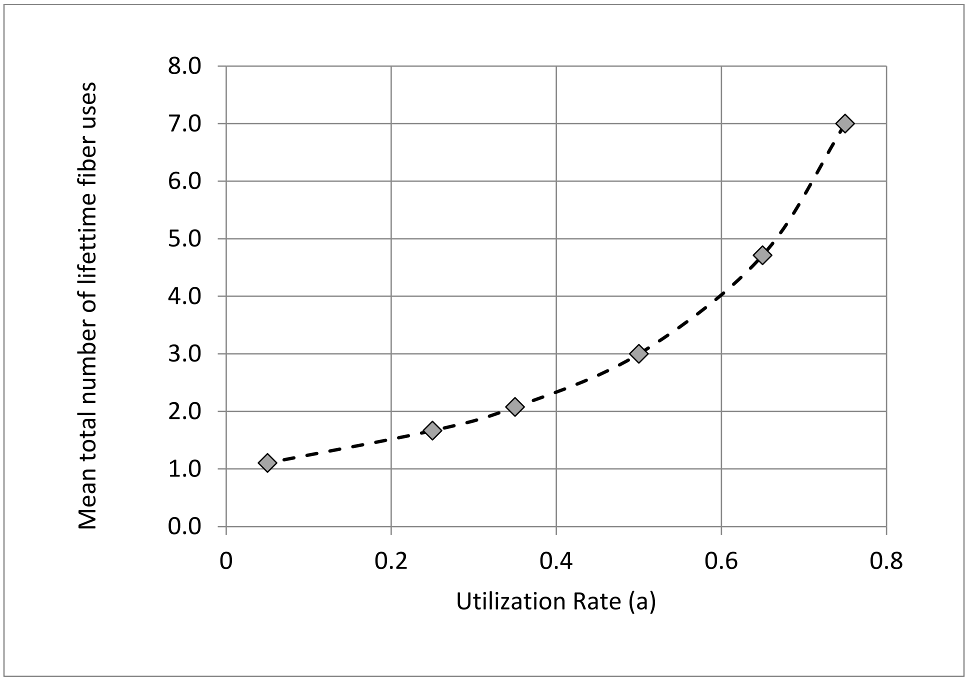

Figure 6. *Mean total number of lifetime fiber uses as a function of utilization rate with the one parameter model*

4.3.2 *Average Number of Times Fiber Can Be Recycled*

The average number of times fiber can be recycled before it has to be discarded due to quality limitations is an important concept because it places an upper bound on the degree to which fibers can be potentially recycled in a functioning fiber cycle. Available laboratory and modeling studies in which this parameter was determined are compiled Table 3.

4.3.3 *Key Messages*

- Recent studies on the recyclability of packaging materials have shown that fibers can be recycled 25 times without significant losses in strength properties.
- The recyclability of 5-7 times often cited in literature may be based upon laboratory recyclability studies on chemical and mechanical pulps, and age distribution models that calculate fiber generations, mean fiber age, and mean fiber future uses for regional markets. The recyclability of 5-7 times should not be construed as an upper limit to recyclability of fiber because of inherent fiber quality degradation.
- The number of recycling cycles in laboratory setups is often limited by fiber losses that occur during the recycling step versus fiber quality degradation issues.
- Results consistently show that fiber changes are most dramatic during the first 2-4 recycles, while fiber property changes with subsequent recycles are less dramatic.
- Table 3 compiles studies on the recyclability of fiber where fiber was recycled multiple times.

Table 3. *Matrix of studies regarding the number of times fiber is recycled*

Reported Number of Times Fiber Is Recycled with Language take Directly from the Publication	Reference	Notes
More than 50	Fisher (2018)	• Results based upon FisherSolve mass balance model. • Specific to old corrugated containers (OCC). • Results based upon fiber compared to product (fiber + additives) or raw material (fiber + non-fiber contaminants). • Not peer-reviewed.
Fiber was recycled 25 times	Eckhart (2021)	• Lab based study on the recyclability of corrugated board typical of the German market in 2018; 80% secondary fibers and 20% fresh fiber [similar to Putz and Schabl (2018)]. • White water circulation was used to minimize fiber loss per recycle to approximately 1% per cycle. • Over 25 cycles there was a decrease in water retention value (WRV) of 14.5% and slight decreases in grinding degree and ash content. • Losses in mechanical properties such as breaking length, bending index, Scott Bond, etc., showed decreases of 5.1 to 11.5% over 25 cycles.
Fiber was recycled 25 times	Putz and Schabl (2018)	• Lab based study on the recyclability of corrugated board typical of the German market in 2018; 80% secondary fibers and 20% fresh fiber. • White water circulation was used to minimize fiber loss per recycle. • After 25 recycles no significant changes could be measured for fiber length and stability properties.

Table 3. *Continued*

Reported Number of Times Fiber Is Recycled with Language take Directly from the Publication	Reference	Notes
Number of fiber recycles ranged between 12-20	Kreplin et al. (2019)	• Lab based study on the recyclability of corrugated base paper. • White water circulation was used to minimize fiber loss per recycle. • Based upon a suite of strength and suspension tests it was concluded that fibers could be recycled at least 12 times.
10-12 times	Grozdits (2006)	• Based upon mill-specific and product-specific claims. • No information on methodology for calculation or reason for recyclability limits beyond "shorter, damaged fiber".
Up to 10 times	Simões et al. (2023)	• Commercial unbleached short fiber (*Eucalyptus globulus*) and long fiber (*Pinus sylvestris*) were tested. • Structural, chemical, and mechanical properties were analyzed. • *E. globulus* maintained the requirements from brown kraftliner and high-performance fluting grades over 10 recycles while *P. sylvestris* lost this rating after the second recycle.
Europe: 3.5 times on average for all paper and board Europe: 6.3 times on average for fibers from packaging The rest of the world: 2.4 times on average for all paper and board	EPRC (2018); ECMA (2018)	• Number is based upon mass balance studies representing 2018 collection and utilization practices in Europe and North America versus a theoretical or practical maximum. • European data from CEPI; international data from RISI. • No information on methodology for calculation. • Not peer-reviewed.

Table 3. *Continued*

Reported Number of Times Fiber Is Recycled with Language take Directly from the Publication	Reference	Notes
Europe: 6.1 times on average North America: 4.6 times on average	Meinl et al. (2017)	• Results are based upon 1-parameter age distribution model representing ~2013 collection and utilization practices in Europe and North America versus a theoretical or practical maximum. • Losses in waste-paper processing are not considered in the model.
Number of recycles in the study was 5	Howard and Bichard (1992).	• The effects of recycling depend on pulp type. • There are a number of causes of recycling effects but one cause dominated for each of the individual pulp types examined, viz: for beaten chemical pulps, loss of swelling ("hornification"); for mechanical pulps, fiber flattening and flexibilizing; for an unbeaten bleached chemical pulp, curl removal. • The effects of recycling occur at different rates in different pulps. For a blend of pulps, the overall effects are dictated by the net result of these different rates. • In these laboratory evaluations, fiber strength and fiber length were unchanged. Nothing resembling "brittleness" was observed. • Recycling without white water recirculation during sheetmaking causes some fines loss which affects the magnitude of the pulp properties. However, with the exception of freeness, the trends in pulp properties are unaffected. This result might possibly be different if the stock was rebeaten between cycles. • Recovered paper quality affects recycled pulp quality.

Table 3. *Continued*

Reported Number of Times Fiber Is Recycled with Language take Directly from the Publication	Reference	Notes
Number of recycles in the study was 6	Ellis and Sedlachek (1993)	• Laboratory study on fiber property development due to repeated drying. • Measured fiber strength properties decreased by 7% after 6 recycles.
Number of recycles from the summarized studies ranged from 4-10	Ferguson (1993)	• This paper summarized the effects of recycling upon mechanical pulp fibers. • The pulping history affects recycling potential. • Calendaring and refining impact fiber strength. • There are a number of causes for recycling effects, but one cause dominates for each pulp type. • Fiber length and strength were unchanged from repeated recycles. Fiber embrittlement was not observed. • Deinking chemicals were not detrimental to fiber strength.
Number of recycles in the study was 5	Law et al. (1996)	• Laboratory recycling study of aspen mechanical and high yield pulp. • The most obvious changes in fiber properties occurred during the first drying cycle and the changes were irreversible. • Subsequent rewetting-drying induced relatively little effect. • Losses in water retention value and fiber bonding capacity were particularly evident with reduction occurring in the first cycle.

4.4 Utilization Rates

Pulp fibers tend to degrade and become less suitable for papermaking with repeated recycle and reuse. Optimum utilization rates exist, given market preferences for paper and paperboard quality, and economic and environmental constraints for a particular region. Several utilization rate concepts can be considered:

- **Maximum technical achievable utilization rate**: Maximum technically achievable utilization rate is what could be achieved in a region if the sector was completely geared toward utilizing recovered fiber while not considering economic or environmental factors and producing the same product mix as the sector is currently producing.
- **Ecological optimum utilization rate**: Ecological optimum utilization rate is the utilization rate in which air, water, and solid residual environmental impacts are minimized (Grossman 2007).
- **Economic optimum utilization rate**: Economic optimum utilization rate is the utilization rate that maximizes economic benefits (Grossman 2007).
- **Practical maximum utilization rate**: Practical maximum utilization rate will be influenced by what is technically achievable, economically possible, and ecologically desirable.

Utilization rate is more closely related to the regional industry structure than to recycling efficiency (COST E48 2018). Wastepaper recovery rates are high in Nordic countries, for example, but utilization rates are low (Berglund et al. 2002; Ervasti et al. 2016). Utilization rates in European countries vary from 5 to 105% (CEPI 2011). Utilization rates in the Nordic countries are 4.9% for Finland, 16.1% in Sweden, and 28.3% in Norway. Utilization rates in European countries whose domestic industry sector is dominated by recovered paper production are high; Hungary is 105.3%, Romania is 91%, and Spain is 82.4% (Blanco et al. 2013). Figure 7 shows the utilization and recycling rates for European countries in 2010 that clearly reflect the concept that utilization rate is more closely related to regional industry structure versus recycling efficiency.

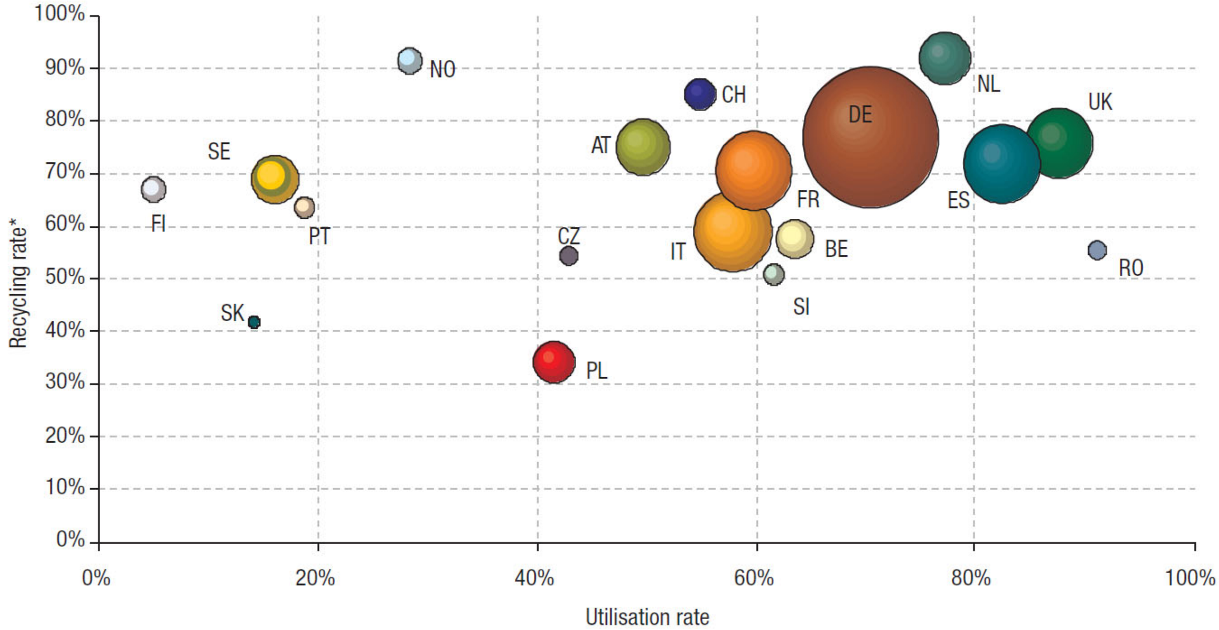

Figure 7. *Utilization and recycling rates[6] for European counties (Blanco et al. 2013; data taken from CEPI 2011)*

Hygiene products, archived graphic papers, or papers contaminated in the waste stream cannot be used again and represent 15-20% of all paper and board production (BIR 2014). Tissue production and writing and bond paper production in the US were approximately 13% in 2021 (AF&PA 2022). The recovery rate in Japan, a country that is highly developed, densely populated, and with effective recycling systems, has a recovery rate of nearly 80% when adjusted for imported packaging (Nordström and O'Kelly 2013). The current utilization rate in Japan is approximately 65%. In addition to non-collectable papers, yield losses at material recycling facilities and recycle fiber facilities limit maximum achievable utilization rates. Yield losses for these steps are treated in subsequent sections within this white paper. Recycled paper and board contain non-fibrous components and water; therefore, indicators such as utilization rate and recycling rate convey optimistic statistics related to fiber recycling (Keränen and Ervasti 2014).

The calculated maximum practical utilization rate will necessarily employ models to project recycling scenarios with greater than current rates, and these models embody simplifying assumptions and require extensive data for parameterization. MIT, with guidance from the American Forest & Paper Association (AF&PA) and input from an array of stakeholders, including NCASI, developed a fiber flow model that calculates optimized fiber flow distributions in the US paper and board sector in response to market perturbations. The AF&PA-MIT fiber flow model was used to calculate maximum utilization rates assuming that all swing mills in the US were geared toward maximizing the utilization of recovered fiber. Maximum utilization rates in the US were also calculated with the Metafore model (Appendix A) and

[6] The recycling rate on the y-axis is the CEPI definition: The ratio between recycling of used paper, including net trade of paper for recycling, and paper and board consumption. It is calculated as "paper for recycling utilisation + net trade" divided by "paper and board consumption," on base paper level.
Country abbreviations: AT: Austria, BE: Belgium, CH: Switzerland, CZ: Czechia, DE: Germany, ES: Spain, FR: France, FI: Finland, IT: Italy, NL: Netherlands, NO: Norway, PL: Poland, PT: Portugal, RO: Romania, SK: Slovakia, SI: Slovenia, UK: United Kingdom

were compared with the AF&PA-MIT fiber flow results (Table 4). Since the time that calculations were undertaken using the AF&PA-MIT fiber flow model, there have been capacity additions from several new recycle fiber facilities in the US, which will increase the calculated weighted average utilization rate with the AF&PA-MIT fiber flow model.

Table 4. *Maximum practical utilization rates of recovered paper*

Weighted Average Utilization (%)	Newsprint	Printing and Writing	Containerboard	Tissue	Notes
47%	-	11%	60%	65%	Calculated from AF&PA-MIT Fiber Flow model (2016 data)
57%	44%	14%	66%	100%	From Table 15: Tissue % change partly because of through air drying (TAD) installations in NA. Newsprint recovered fiber 60% in 2008 and 4 percent in 20181

https://www.recyclingtoday.com/article/recycled-pulp-possibilities/

Ecological optimum utilization rates have only been considered from a conceptual standpoint because of the challenges in valuing ecological impacts (Grosssman 2007). Ecological optimum utilization rates can be exceeded from a greenhouse gas emission standpoint if additional recycling production is reliant upon high-carbon grid electricity (van Ewijk et al. 2021). Chemical pulping utilizes high percentages of biomass fuels for self-generation of steam and electricity with low GHG emission properties, while recycle pulping is dependent upon purchased fuel (usually fossil fuels) and purchased electricity for steam and electricity needs. Byström and Lönnstedt developed a combined optimization and simulation model of the European fiber system and used it to determine that the environmental optimum for continental Europe and Scandinavia is achieved at lower utilization rates than the maximum technically achievable utilization rate (1997).

Figure 8 shows trends in recovery rates for the US market. Figure 9 shows trends in utilization rates for the US market. Utilization rates have increased from 36.9% in 2012 to 43.8% in 2021. Recovery rates have shown a smaller increase over the same period; from 65% in 2012 to 68.1% in 2021. Recovery and utilization rates for other regions are provided in Appendix B.

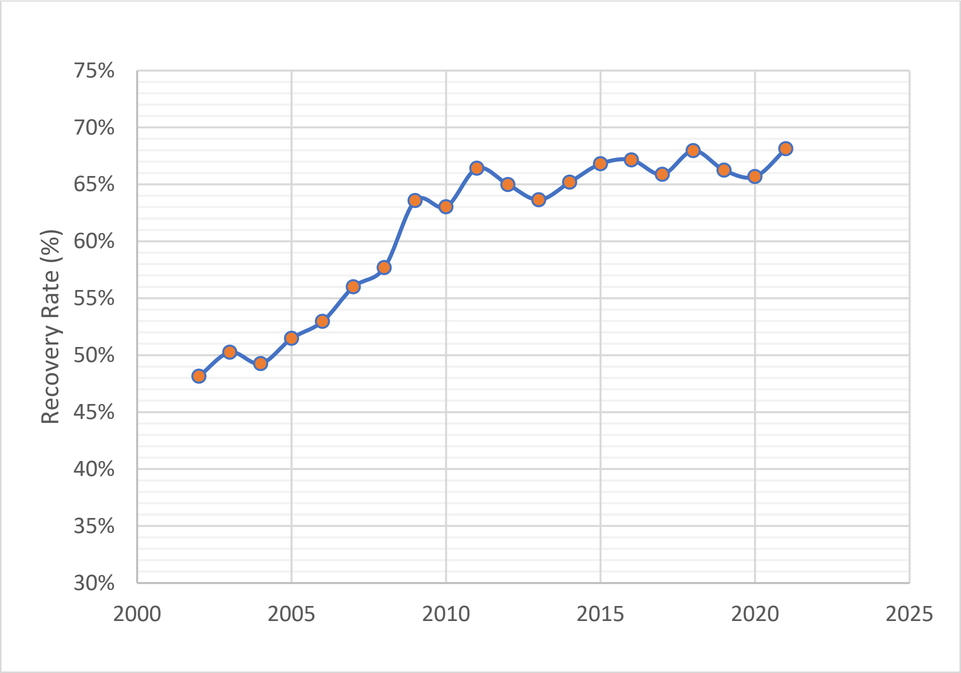

Figure 8. *US pulp and paper sector recovery rates over time (AF&PA 2022)*

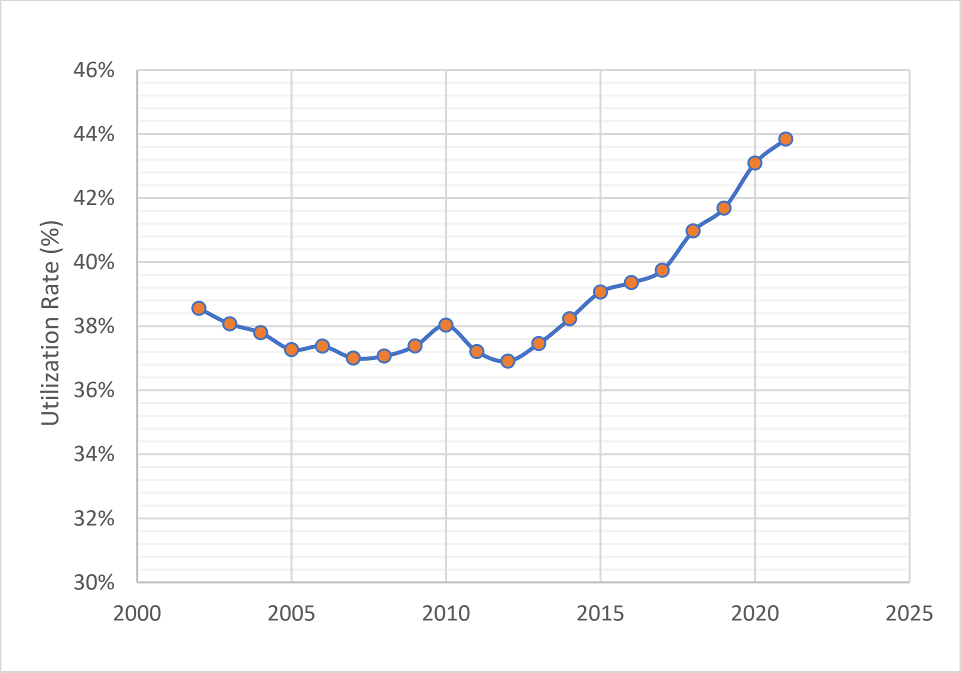

Figure 9. *US pulp and paper sector utilization rates over time (AF&PA 2022)*

4.4.1 *Key Messages*

- Recovery and utilization rates vary by paper grade.
- Utilization rate is more closely related to the regional industry structure than recycling efficiency.
- Quality, economics, and availability of recovered fiber are the three most important elements to determine regional utilization rates (Keränen and Retulainen 2016)

4.5 Yield Losses at Recycle Mills

A certain amount of incoming material to recycle mills is removed during processing to produce final products with specific quality specifications. The difference between incoming material and final product on a mass basis is termed yield loss. Total yields in recycle mills range from ~50 to 90%, depending on fiber stock, recycling process, and product being manufactured. Table 5 shows yields for various types of recycled pulp production by recovered fiber input and final product (Hamilton and Leopold 1987). Similar yield information is provided in Table 6 for various grades of recycled pulp production, but capturing more recent designs for pulp recovery at recycle mills (Göttsching and Pakarinen 2000). Yield losses originate from fibrous losses as well as non-fibrous losses from materials such as plastics, staples, fillers, stickies, laminates, starch, and coatings (Keränen and Ervasti 2014; De Jong 2008; De Jong et al. 2013). Non-fibrous contents for certain grades can be substantial [the non-fibrous content of printing and writing papers in Europe was 23% in 2010 (Keränen and Ervasti 2014)].

Table 5. *Recycled pulp mill yields (Hamilton and Leopold 1987)*

Input	Output (%)			
	Newsprint	Coated and Uncoated Printing	Tissue	Multi-Ply Board
Newspaper	85		85	90
Coated groundwood		53 - 65	53 - 65	90
Super mixed paper		65	65	90
OCC				90
White ledger		80	80	95
White soft shavings		75	75	90
Tabulating card		93	93	95
Polyethylene coated		85	85	90

Table 6. *Ranges of pulp yield for recovered paper processing (Göttsching and Pakarinen 2000)*

Product Type	Yield
Packaging papers and board	90-95%
Specialty papers	70-95%
Graphic papers	65-85%
Market DIP (wood-containing)	80-85%
Hygienic papers	60-75%
Market DIP (wood free)	60-70%

Yield losses at recycled fiber facilities can be grouped into two major categories (rejects and sludges). Table 7 shows yield loses by major categories for various recycled fiber products. Sludges are the greatest contributor to overall facility yield losses.

Table 7. *Amounts of rejects and sludges by recovered paper grade and paper product (Göttsching and Pakarinen 2000)*

Produced paper	Recovered paper grade	Amount of total waste (% by dry weight)	Amount of waste (% by dry weight)			
			Rejects (Heavy-weight & coarse)	Rejects (Light-weight & fine)	Sludges (Flotation deinking)	Sludges (White water clarification)
Graphic paper	News, magazines	**15-20**	1-2	3-5	8-13	2-5
Graphic paper	Superior grades	**10-25**	< 1	≤ 3	7-16	1-5
Hygienic paper	Files, office paper, ordinary medium grades	**28-40**	1-2	3-5	8-13	15-25
Market DIP	Office paper	**32-40**	< 1	4-5	12-15	15-25
Liner, fluting	Sorted mixed recovered paper, supermarket waste	**4-9**	1-2	3-6		0-1
Board	Sorted mixed recovered paper, supermarket waste	**4-9**	1-2	3-6		0-1

4.5.1 *Containerboard Mills*

Containerboard facilities utilizing old carbon containers (OCC) should be capable of achieving yields of 90-93% on an oven dry basis, Table 8 (Fleming 2014). Yield losses are derived from cleaning and screening rejects as well as pre-treatment steps to remove non-fibrous contaminants. Containerboard facilities tend to have little losses from sludges.

Table 8. *OCC system yield losses (% of feed, oven-dry basis) (Fleming 2014)*

Equipment	Yield Loss
Pulper trashwell	0.25 – 0.65%
Pulper detrasher	1.5 – 2.0%
Pulper rag rope	0.75 – 1.0%
HD cleaners	0.5 – 0.75%
Coarse screening	0.75 – 1.5%
Forward cleaners	0.75 – 1.25%
Fine screening	1.0 -1.4%
Lightweight cleaning	0.40 – 0.65%
Totals	**5.9 - 9.2%**

4.5.2 *Deink Mills*

Deinking technologies are important for the production of graphic papers with more stringent optical property requirements for the final products. Yield losses at deink mills will be greater than at OCC facilities, and yield losses of 30% are not uncommon. Typical yields for deinking of different raw materials are provided in Table 9.

Table 9. *Typical deink mill yields for various raw materials (Göttsching and Pakarinen 2000)*

Process	Yields
Newsprint and improved grades	78-85%
High-grade writing and printing papers	65-70%
Tissue	63-70%
Market DIP	60-65%

Kotanen et al. (2014) reviewed the resource efficiency of deinked pulp production and compiled yield loss information by process stage from several authors, shown in Table 10. Consistent with Table 7, flotation sludge removal is usually the largest contributor to yield losses at deink facilities. Kotanen et al. (2014) provide a schematic of a single line deink mill designed to minimize yield losses (Figure 10). Yield losses for this process configuration are ~15%, which can be considered current state-of-the-art for deink yield minimization.

Table 10. *Yield losses by process stage in deink pulp production*

Process Stage	Materials Removed	Amount (%) by dry weight	Valuable materials in reject streams
Pulping	Unusable material (e.g., wet strength paper, metals, and plastic)	0.5-15	None (when pulping working properly)
Coarse screening	Staples and flakes	0.5-2.0	
Fine pre-screening	Macrostickies, dirt specks	0.5-2.0	Fibers
Flotation	Ink, microstickies	8-16	Filler
Fine screening	Macrostickies, dirt specks	0.5-2.0	Fibers
Cleaning	Sand	0.5-1.0	Fibers
Thickening/DAF	Ink, extractives	1-5	Fines

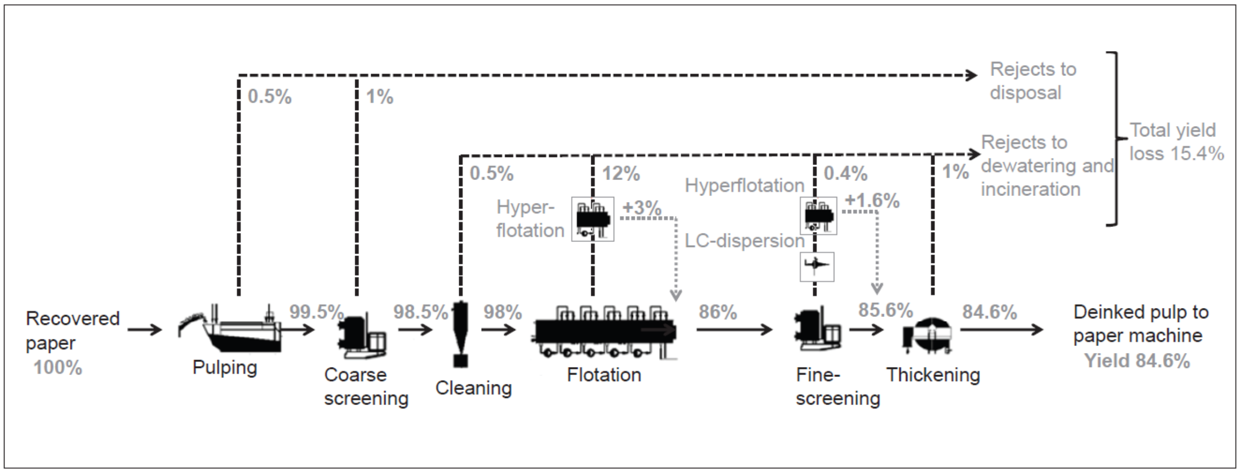

Figure 10. *A deinked pulp line with material recovery to reduce yield losses (Kotanen et al. 2014)*

The fiber yield within domestic containerboard facilities may be dependent upon the origin of the old corrugated containers (OCC). Mayovsky studied the amount of usable fiber from OCC originating from various countries (Mayovsky 1995). The amount of usable fiber contained in the OCC coming into the processing plant (weight of boxes minus the weight of contaminants, starch, ash, and moisture) from Asian countries averaged 76.6%, as illustrated in Table 11 below. Average yield from domestic OCC was 85.3% using the same test approach.

Table 11. *Average OCC yields from Asian countries and domestic yields (Mayovsky 1995)*

Contaminants	Asian Countries	Domestic
Staples and tapes (%)	1.08	1.00
Ash (%)	7.93	1.7
Starch (%)	6.60	~2.0
Fines (mm)	19.7	15
Overall Potential Yield (%)	76.6	85.3

4.5.3 *Key Messages*

- Total yields in secondary fiber recycling range from ~50 to 90% and depend upon the raw material type, raw material quality, recycle mill configuration, the type of products produced, and the origin of the recycled fiber.
- Facility yield losses are from fibrous and non-fibrous contributions.
- Containerboard mills tend to have the lowest yield losses of the major recycled fiber product types.
- Deink mills producing higher optical quality products or market pulp have the lowest yields of the major recycled fiber product types.
- The most important parameters to determine facility yield are repulpability, yield of fibrous material, amounts of coarse rejects, flake content, and stickies, and technical quality. (derived from AF&PA's Design Guidance for Recyclability[7] and CEPI's paper-based packaging recyclability guidelines[8]).

4.6 Market Changes Affecting Recyclability

4.6.1 *Single stream recycling*

Single stream recycling is a system through which all recyclables are placed in a single bin for recycling. It has become increasing popular in the US since the first single stream recycling system was implemented at a US municipality in 1989. With the single stream recycling concept, materials are sorted at the

[7] AF&PA's Design Guidance for Recyclability: https://www.afandpa.org/sites/default/files/2021-08/AFPADesignGuidanceforRecyclability_FINAL_031621.pdf
[8] CEPI paper based packaging recyclability guidelines: https://www.cepi.org/wp-content/uploads/2020/10/Cepi_recyclability-guidelines.pdf

material recycling facility (MRF) versus at the household. Total unusable material at material recovery facilities can vary from 5 to 20% (Emerson 2004; Miranda et al. 2011; Miranda et al. 2013). Contamination rates at Waste Management (the world's largest waste disposal company and largest in the US[9]) material recycling facilities averaged 16% in 2021 (Waste Management 2022 Sustainability Report[10]). Several authors (Pressely et al. 2015; Emerson 2004; Damgacioglu et al. 2020; Tonjes et al. 2018; Aphale et al. 2015; Miranda et al. 2011; Miranda et al. 2013) have investigated the impacts of single stream recycling and their findings are essentially consistent:

- Single stream recycling tends to increase set-outs (amount of material placed in recycle bins from households) for recycling.
- Single stream recycling tends to increase non-recyclable items in recycling bins.
- Single stream recycling tends to increase residuals.
- Processing costs tend to be higher at the MRF, but collection costs tend to be lower.

4.6.2 *Through Air Drying*

Through air drying (TAD) is a tissue drying technology for the production of high-quality tissue and towel products. Hot air passes directly through the wet porous sheet to create high drying rates compared to conventional tissue drying. For high-quality consumer tissue products, 100% fresh fiber is normally utilized. The tissue machine former often will have layering capability such that a hardwood fiber (eucalyptus for the softest products) is placed on the outer, consumer facing, layer while softwood fresh fiber is used in the inside layer for strength. Northern softwood kraft pulp such as spruce is often used. For lower quality products recycled fiber may be used, and fiber selection is determined by cost and quality constraints. Figure 11 shows a modern tissue drying system with two TAD drums in series followed by a Yankee dryer.

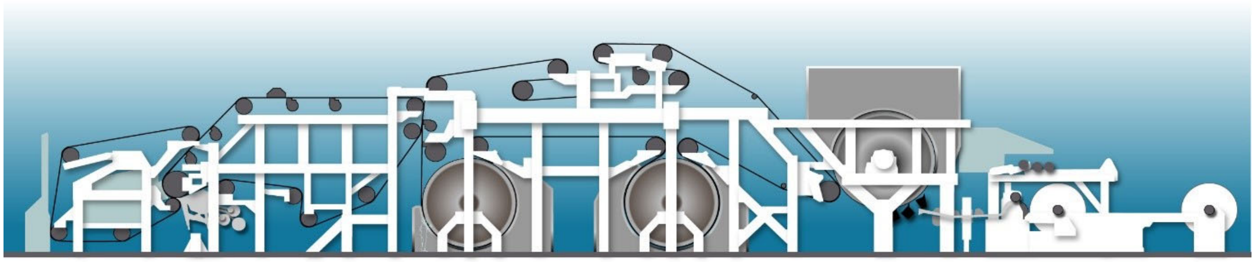

Figure 11. *Tissue dryer with two through air dryer drums in series followed by a Yankee dryer*[11]

[9] In the United States, WM recycled more than 15 million tons of recycled material across 135 facilities in 2022, with about 7.79 million tons of that recycled paper.
[10] https://sustainability.wm.com/downloads/WM_2022_SR.pdf
[11] https://www.tissuestory.com/wp-content/uploads/2017/08/4.jpg

In 2013, TAD installation represented 30 percent of the installed tissue capacity in the North American market (Gervais 2013). In 2022, the installed TAD capacity in the US had risen to 44% of installed capacity, shown in Table 12. Due to the fresh fiber requirements for high quality TAD tissue and towel production, the expansion of TAD capacity in the tissue and towel market has placed downward pressure on utilization rates of recycled fiber within the tissue and tower sector.

Table 12. *Paper machine technology capacity for US tissue and towel (FisherSolve Next)*

	Capacity (short ton/year)	Representation (%)
TAD installations	3,960,597	44%
Conventional	5,061,237	56%
Total	9,021,835	100%

4.7 New Capacity Additions in the United States

FisherSolve Next[12] compiles announced capacity changes by major grade. Table 13 summarizes the announced capacity changes for the US market by major grade. Between 2020 and 2030 there will potentially be 5.75 million short tons of cartonboard, containerboard, and packaging paper capacity coming online. There will potentially be about 4.0 million short tons of printing and writing and specialties capacity being removed from the market. It is expected that these market changes will decrease the demand for fresh fiber and increase the demand for recycled fiber within the US, given the distribution of recovered fiber across these product types.

Table 13. *Announced capacity changes by major grade between 2020 and 2030 (FisherSolve Next)*

Major Grade	Capacity Changes
Captive Slurry Pulp	59,033
Cartonboard	1,439,901
Containerboard	4,082,970
Market Pulp	691,847
Newsprint	285,509
Packaging Paper	251,440
Printing and Writing	(2,991,762)
Specialties	(1,170,929)
Tissue and Towel	753,841

[12] https://www.fisheri.com/

Assuming that new cartonboard, containerboard, and packaging paper capacity uses available domestic recovered paper and board for production needs, it is calculated that once all on the new containerboard capacity comes online, utilization rates within the US will approach 50% (at the expense of less exported recovered fiber). Table 14 shows the calculated domestic utilization rate considering new capacity additions and the reduction in exports of recovered paper required to achieve a 50% domestic utilization rate.

Table 14. *Potential effect on domestic utilization rates with increased containerboard capacity*

Year	Domestic Utilization Rate	Export of Recovered Paper (thousand short tons)
2021	44%	18,000
2030 (considering announced capacity changes in Table 13)	48%	14,600
2030 (AF&PA goal)	50%	13,500

4.8 Exports of Recovered Paper

International trade of collected recovered paper and of imported and exported paper and board products has important influences on the domestic utilization rate of recovered fiber because trade affects quality, economics, and availability of recovered fiber, which are the three most important elements that determine regional utilization rates (Keränen and Retulainen 2016). Berglund et al., in a series of papers, developed an econometric model to determine demand and use of recovered paper and determined that waste-paper availability is an important determinant of domestic utilization rates (2002; 2003a; 2003b). Figure 12 shows that Asian countries are currently the destination for over 75% of recovered paper that is exported from the US.

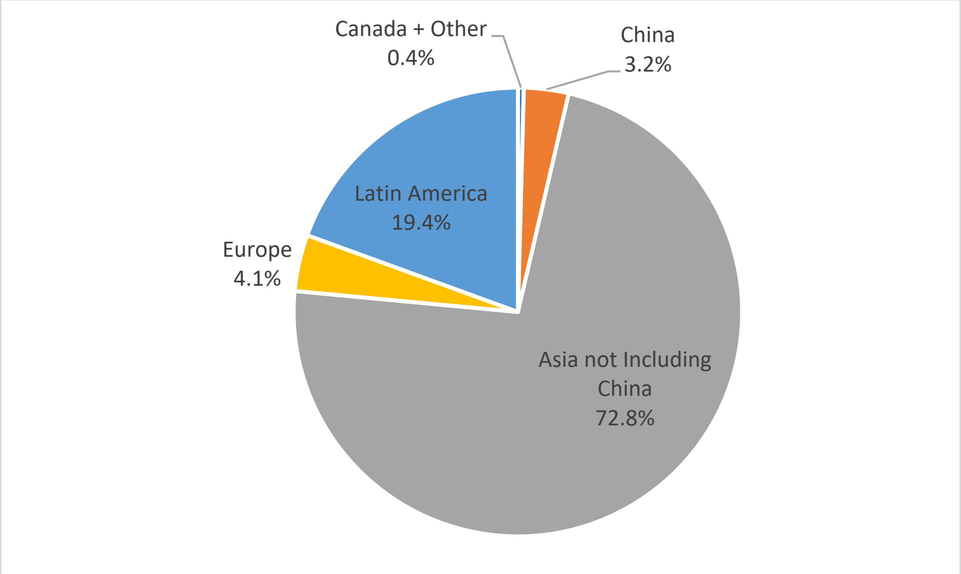

Figure 12. *2021 recovered paper net exports (AF&PA 2022)*

Figure 13 shows the impact of net exports of recovered paper on domestic utilization rates. Net exports of recovered paper peaked in 2011 at approximately 22 million short tons and have been decreasing since. During the same period, recovery rates have increased, but more modestly, shown in Figure 14. Increases in recovery rates, decreases in net exports of recovered paper, and capacity expansion of facilities that can utilize recovered paper have led to increases in domestic utilization rates since 2012.

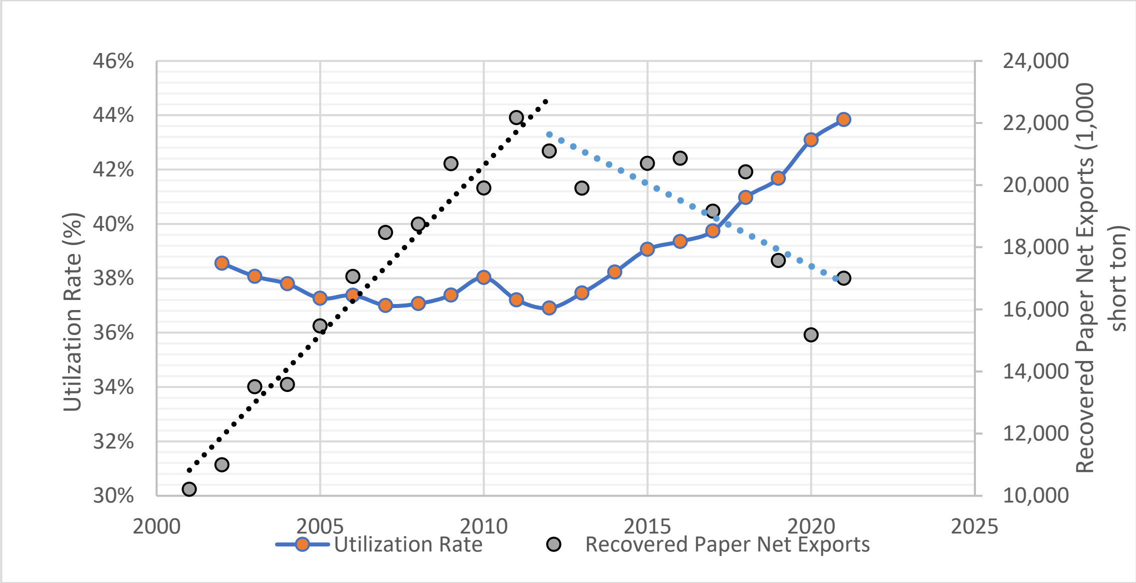

Figure 13. *Impact of net recovered paper exports on domestic utilization rate*

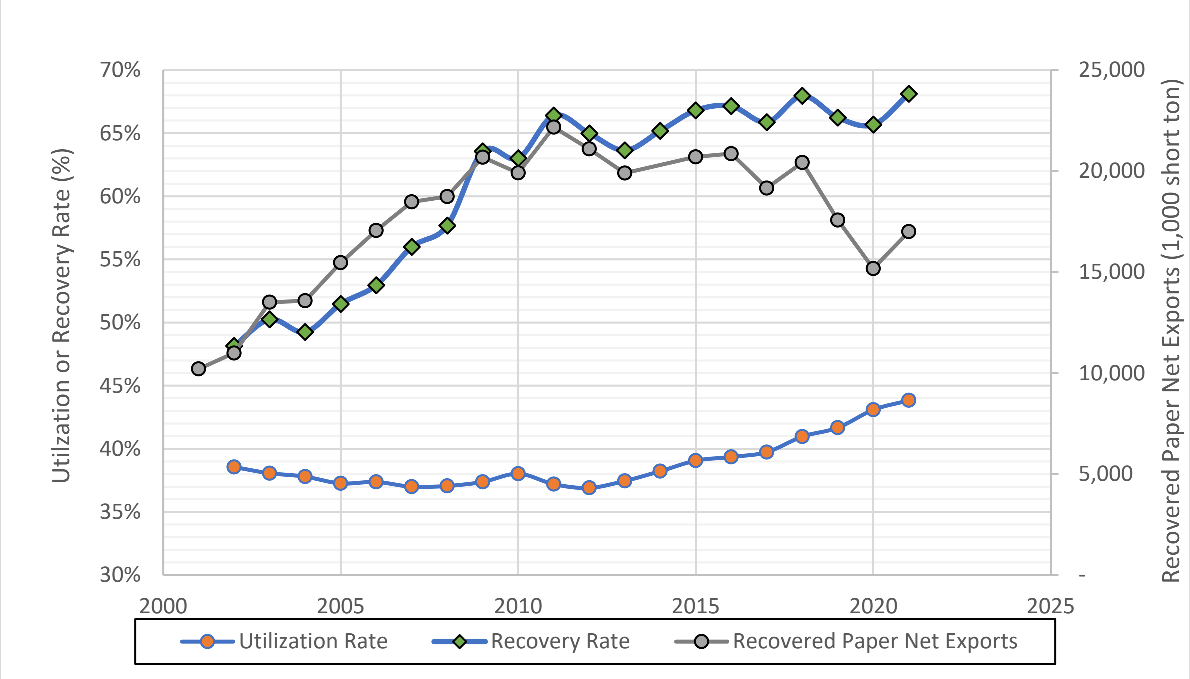

Figure 14. *Divergence of recovery rates and net exports in the United States since 2013 and impact on utilization rates*

5.0 Conclusions

This NCASI white paper on the recyclability of paper and paperboard in the United States provides sustainability information related to recycled fiber, such as fiber longevity, fresh fiber requirements for a functioning fiber cycle, age distribution of products, average number of times fiber can be recycled, utilization rates, and market changes and challenges affecting recyclability. Significant market changes within the last decade have led to higher domestic utilization rates. Domestic utilization rates should continue to increase as new containerboard capacity comes online, with corresponding reductions in exported recovered paper.

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APPENDIX A: Metafore Model

Longevity of the Fiber Cycle in Months

The longevity of the fiber cycle, i.e., the amount of time the fiber cycle would operate **in the absence of fresh fiber**, was determined using the equations used in the Metafore document, which assume that fiber can be recycled six times before it becomes unusable, and a declining fiber yield equation based upon the number of times the paper or board has been recycled. These equations can be derived from Figure 15, which is a modified mass balance for domestic recycle fiber production assuming no fresh fiber input. Terminology in Appendix A is consistent with terminology used in the Metafore document.

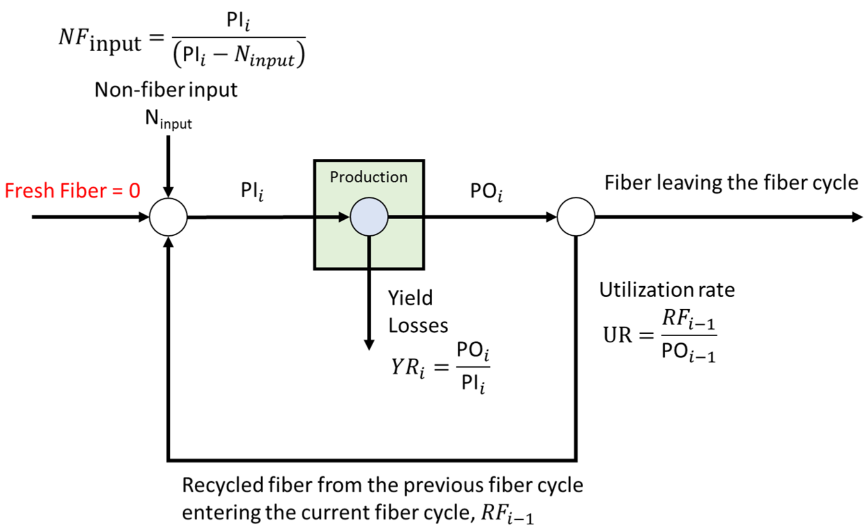

Figure 15. *Fiber cycle mass balance for cycle i*

The paper output for cycle *i* is:

$$PO_i = PO_{i-1} \cdot UR \cdot YR_i \cdot NF_{\text{input}}$$

PO_i: Paper output for cycle i

UR: Recovered paper utilization rate (the amount of recovered paper used for domestic paper and paperboard production as a percentage of total domestic paper and paperboard production).

YR_i: Yield rate for each successive reuse of fiber

NF_{input}: A factor to estimate the portion of non-fiber input in paper products, e.g., NFinput = 1.1 I implies that non-fiber inputs are 10% by weight of the paper product

Total annual paper output from recovered fiber can be obtained by summing the paper output for all (six) paper cycles.

$$TPO = \sum PO_i$$

TPO: Total cumulative paper output from using recovered fiber

i: The number of times the fiber is recycled

The longevity of the fiber cycle is the ratio of the cumulative paper output from recovered fiber to the production consumption. As in the Metafore document, annual statistics are used because they are the numbers most readily available. Using annual statistics for calculation of fiber longevity is conservative because the approach assumes one year's worth of product inventory can be used to supply the fiber cycle.

$$L = (\text{TPO}/\text{CONS}) \cdot 12$$

L: The longevity of the fiber cycle in months

CONS: Annual production

Required fresh fiber to maintain the fiber cycle at a given level of total fiber output for paper

$$\text{VF}_i = \text{TFO} - \sum_{\substack{i=n,\dots,1 \\ c=1,\dots,p}} RF_{i,c}$$

VF_i: Fresh fiber input for a given cycle

TFO: Total fiber output

$\text{RF}_{i,c}$: The amount of recycled fiber recovered and reused from previous production cycles, where i is the number of cycles and c is the number of passes a fiber makes.

To make use of the equations, major grade data are required for production (PO_1 and CONS), utilization rates (UR), yield factors (YR), and non-fiber input factors (NF_{input}). Paper grade production amounts and current utilization rates can be found in US paper and board statistics from AF&PA (2022) or from various public sources (FAO 2022; FAO 2022b; Howard et al. 2016; and Skog et al. 2011). Maximum utilization rates, yield factors, and non-fiber input factors are considered relatively constant and are provided in Table 15.

Table 15. *Paper grade variables for use in the Metafore Model*[13]

Variables	Newsprint	Printing and Writing	Containerboard	Tissue	Sum and Weighted Average
Maximum Utilization Rate of Recovered Paper	44%	14%	66%	100%	57%
Yield Factor	85%	70%	88%	75%	83%
Non-fiber Input Factor	1.004	1.166	1.019	1.001	1.05

[13] From "The Fiber Cycle Technical Document," Metafore 2006

APPENDIX B: Recovery and Utilization Rates in Other Regions

Available information on recovery rates with Canada are provided in the Figure 16, and in Europe in Figure 17 and Figure 18.

Canada

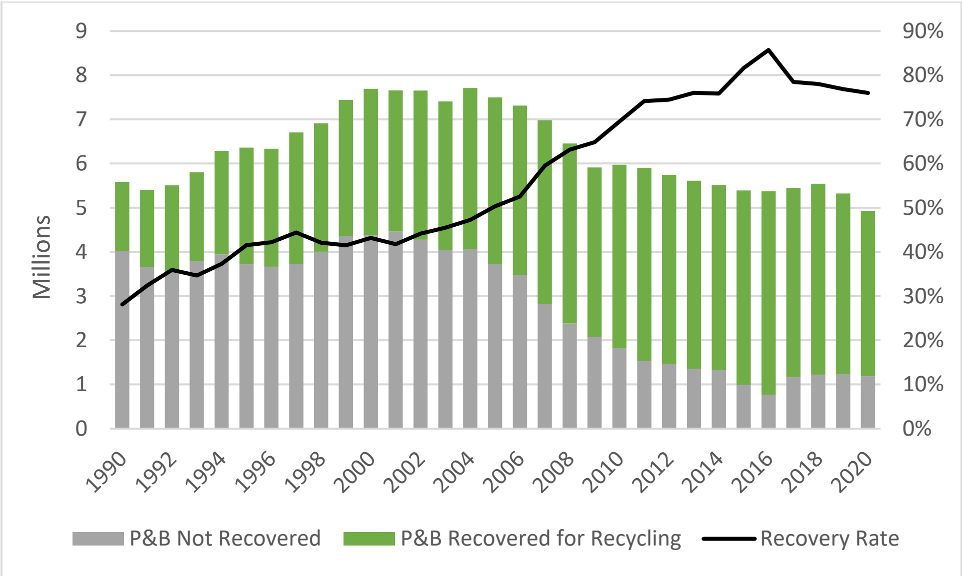

Figure 16. *Canadian paper and paperboard recovery rate over time (Numera Analytics 2021)*

Europe

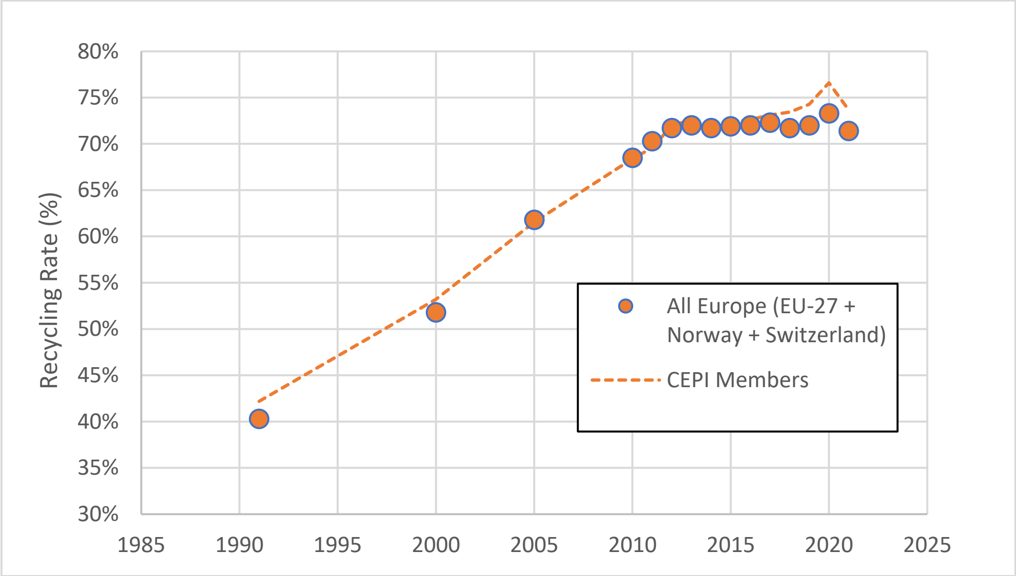

Figure 17. *Recycling rate over time in Europe (CEPI 2023)*

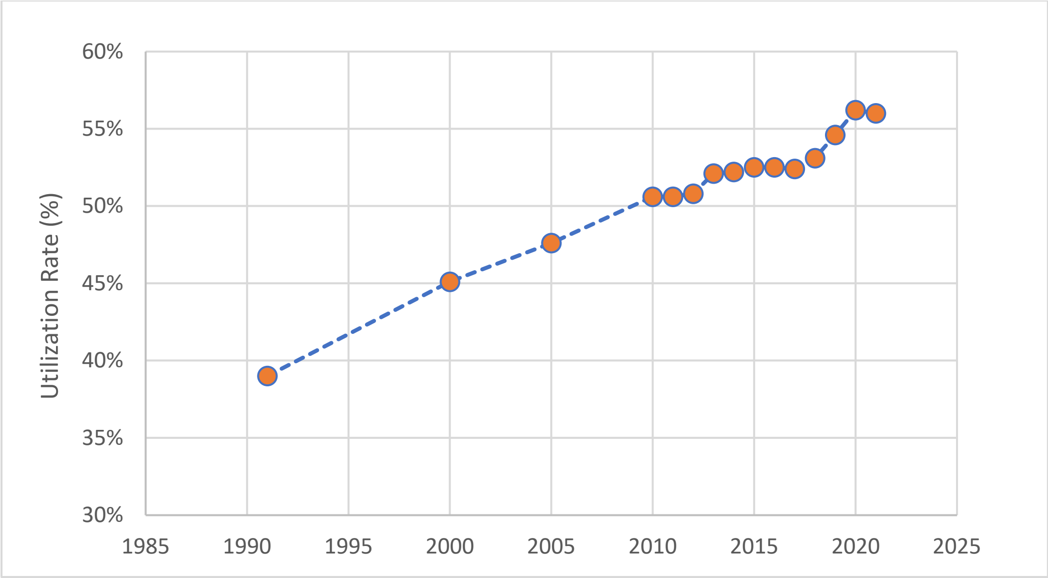

Figure 18. *Utilization rate over time in CEPI member countries (CEPI 2023)*